Horticultural Uses for Flue Gas Desulfurization Gypsum

by

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Abstract

Gypsum (calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$)) is a naturally occurring colorless and odorless solid mineral, with a very fine particle size. Gypsum is usually mined from natural deposits in the earth, but can also be produced synthetically when the exhaust gases from the burning of high sulfur-containing coal are released into calcium carbonate filters, a form known as flue gas desulfurization gypsum, or FGD gypsum. The natural form has been used for hundreds of years as a type of fertilizer, yet the synthetic form is not widely used within agriculture. Three studies evaluated the horticultural uses of FGD gypsum including: occurrence of blossom end rot on greenhouse tomotoes; the production of three greenhouse crops that included fern, geranium, and petunia; and stem strength of poinsettias. Most of the experiments performed used a rate of 3.26 kg/m^3 (5.5 lbs/yd^3) of FGD gypsum incorporated into the substrate mix, increasing by 3.26 kg/m^3 (5.5 lbs/yd^3) up to 19.58 kg/m^3 (33 lbs/yd^3). All treatments were compared to a control of no additional FGD gypsum. The FGD gypsum was incorporated into the soil mix and the plants were grown to a marketable size, or in the case of tomato, a harvestable and marketable size and color. Results varied across all experiments, with no detrimental effects observed even at the highest FGD gypsum levels. In tomato experiments, there was a reduction in the occurrence of blossom end rot, and increased in fruit weight and number were observed with increasing FGD gypsum level. There were varying results for the three greenhouse crops. One of the most promising results in the poinsettia experiments showing greater stem strength at higher rates of FGD gypsum were added. Throughout all experiments, plants were tolerant of the high FGD gypsum rates, and results indicate FGD gypsum could be a suitable replacement for lime as a calcium source when a substrate pH adjustment is not needed. However, plant growth and development in response to supplemental FGD gypsum in our greenhouse studies in soilless substrates were not as distinct as responses reported from studies using mineral soils. Therefore, we conducted a final study to evaluate the stability of supplemental FGD gypsum in two soilless substrate blends commonly used in greenhouse crop production. Our results show that FGD gypsum is rapidly leached from the soil column and does not remain as effective in soil solution as expected. Therefore, FGD gypsum does not appear to be to be suitable for long-term supply of calcium and sulfur, and is not likely to provide reduction of phosphorus in leachates from soilless substrates. Specifically, our data shows that FGD gypsum incorporated into a soilless substrate washes out of the container in less than 10 irrigation events when a standard irrigation regimen target of 10% leaching fraction is used.

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CHAPTER I

Horticultural Uses for Flue Gas Desulfurization Gypsum

Introduction

Gypsum (calcium sulfate dihydrate ($CaSO_4 \cdot 2\ H_2O$)) is a naturally occurring colorless and odorless very fine textured solid mineral, with a particle size that is typically finer than 50 µm (Norton, 2009). Gypsum is usually mined from natural deposits in the earth, but can also be produced synthetically when emissions from burning of high sulfur-containing coal are passed through a calcium carbonate slurry filter. In 2016, the mined form of gypsum accounted for an estimated 11.5 million tons in the United States, with the synthetic form also accounting for an estimated 11.5 million tons (USGS, 2016). Of the total gypsum produced in the U.S., either mined or synthetically produced from coal-fired electic and industrial plants, an overwhelming majority is used in the wallboard industry. Other uses for gypsum, either naturally occurring or produced via synthetic means include cement additives, road construction, structural backfills for land construction, and agriculture uses.

Coal production in the United States has greatly increased over the past several decades, with 2016 coal production being over 700 billion short tons (United States Energy Information Administration, 2017), with much of the production of coal being used for creating electrical power. Contained within the hundreds of coal-burning power plants throughout the United States are devices that capture the sulfur dioxide (SO_2) emissions from burning coal (Fig. 1). The Clean Air Act Amendments of 1990 mandated that facilities that produce SO_2 and other pollutants, particularly coal-fired power plants, be equipped with flue gas desulfurization (FGD) technology, commonly referred to as scrubbers, to improve the the efficacy and removal efficiency of removing pollutants from the emissions (Popp, 1990). These scrubbers are used to remove the SO_2 - containing emissions of coal-fired power plants that burn high sulfur coal, thereby eliminating the contaminants which would otherwise enter the atmosphere and cause detrimental effects to the environment.

As coal is burned for electricity production, the exhaust gases (or flue gas) are forced into the scrubber works by spraying a slurry of limestone (calcium carbonate, $CaCO_3$) and water into a large chamber where the calcium in the limestone reacts with the SO_2 in the flue gas. Once sulfur-containing coal is burned and produces SO_2, the exhaust gas passes through the scrubber where a spray mixture of limestone (or other chemical reagent) and water reacts with the SO_2. The reaction enables the SO_2 to be removed before it is released into the atmosphere. When SO_2 combines with limestone, the primary byproduct is calcium sulfate, commonly known as synthetic gypsum, or flue gas desulfurization (FGD) gypsum. This synthetic gypsum is used in the manufacturing of wallboard and cement, and as a soil amendment in agricultural and construction applications (Duke Energy, 2017).

There are many types of byproducts referred to as coal combustion residuals (CCRs), materials produced primarily as a byproduct from the burning of coal in coal-fired power plants (USEPA, 2015). Some of the products produced include fly ash, bottom ash, boiler slag, and the resulting FGD material. The FGD gypsum may then go through a washing process to remove water-soluble contaminants such as boron (B) or in some cases, mercury (Hg), if it is going to be used in the wallboard industry, though the washing process is not typically used for gypsum intended for agriculture use. The resulting gypsum must then be dewatered through the use of centrifugation and vacuum filtration. The result is a high quality gypsum that can be used for several different industrial and agriculture uses (Chen and Dick, 2011). FGD gyspsum may contain distinguishable levels of impurities at trace levels, though it has a much higher purity than mined gypsum. Because FGD gypsum is almost pure and comparable to mined gypsum there is a significant potential for greater application use in agricultural settings, specifically horticultural use.

In 2008, production of FGD gypsum was predicted to double over the next several years (USEPA, 2008), and United States domestic production of crude gypsum was estimated to be 15.5 million tons (USGS, 2017) . Currently, about 7.2 million tons of gypsum is used for cement production or in agriculture (USGS, 2017). According to the American Coal Ash Association, only about 4% of the FGD gypsum produced in the United States is used for agricultural purposes (ACAA, 2014). Gypsum products are categorized as either calcined or uncalcined. Calcined gypsum is produced domestically from mined crude and synthetic gypsum to manufacture wallboard and plaster products. Uncalcined gypsum is used to produce portland cement and in agriculture. Uncalcined gypsum use in agriculture was estimated to be approximately 3.01 million tons in 2015, which is an increase of 39% from that in 2014 (USGS, 2015). More than 99% of the calcined gypsum was used in the production of prefabricated products, most of which consisted of wallboard (USGS, 2015). Although many other industries utilize the majority of FGD gypsum produced, agriculture represents the smallest percentage of current usage, but offers one of the greatest potentials for use of this byproduct.

Agricultural Use of Gypsum

Gypsum has been used for hundreds of years and was one of the earliest nutrient sources for plant nutirents that dates back to the late 18th century (Crocker, 1922). Gypsum has been shown to improve overall plant growth, improve soil physical and chemical properties, sodic soil reclamation, and supply the essential plant nutrients, Ca and S (Chen and Dick, 2011).

The Ca and S in gypsum are readily utilized as nutrients in plants due to the solubility of gypsum ($2.5\ g \cdot L^{-1}$ at 20ºC) and small and uniform particle size (Chen and Dick, 201; Chen, et al., 2005). Supplemental Ca provided by gypsum has been shown to improve yield and seedling survival of runner peanut crops (Adams et al., 1993). Increasing rates of Ca applied to soil reduced the incidence of blossom end rot (BER) in ‘Charleston Gray’ watermelons (Scott et al., 1993). Other studies using gypsum to supply Ca to plants include Menge, et al. (1994), which showed increased plant growth, yield, and root growth, as well as reduced *Phythophthora citricola* incidence on avocado plantings, and Nemec and Lee (1995) observed gypsum-amended field soil reduced root rot caused by *P. parasitica* in citrus. Gypsum to supply S has been used where S is depleted due to factors such as little or no S in fertilizers (Scherer, 2001) and where there was less S deposition from the atmosphere (Fig. 2) (National Atmospheric Deposition Program, 2015). With deficiencies of S increasing worldwide (Chibber, 2007), gypsum could provide needed S on deficient soils (Chen et al., 2005).

Exchangebale S and Ca has been shown to ameliorate the effects of subsoil acidity by reducing Al^{3+} toxicity (Farina and Channon, 1998; Sumner, 1993; Wendell and Ritchey, 1996). Acid topsoils can be improved through incorporation of limestone, however liming has little immediate effect on the subsoil layer due to slow movement down through the soil profile (Sumner, 1993). Adding $CaSO_4$ and $CaSO_3$ FGD byproducts has been shown to reduce Al^{3+} toxicity in acidic subsoil layers, increasing usable soil depth for plant roots and plant productivity (Wendell and Ritchey, 1996). Toma et al. (1999) observed long-term effects of adding gypsum to soils and reported a reduction in exchangeable Al in the subsoil profile 16 years after application. The detoxification of Al^{3+} and increased supply of Ca^{2+} through incorporation of gypsum into the soil can also improve rooting depth (Farina and Channon, 1998; Sumner, 1993; Wendell and Ritchey, 1996).

High sodic soil reclamation involves replacement of exchangeable Na^{+} with Ca^{2+} using a Ca amendment (Oster and Frenkel, 1980), and the most common amendment used for sodic soil reclamation is gypsum (Chen and Dick, 2011). These soils are prone to clay dispersion resulting in the formation of impermeable surface sealing, and decreased soil profile hydraulic conductivities that adversely affect water, solute and air movement, soil erodibility, and plant growth (Shainberg and Letey, 1984). Several experiments

(Miyamoto et al., 1975; Shainberg et al., 1989; U.S. Salinity Lab, 1954) have shown incorporation of mined gypsum has been used for many years for high sodic soil reclamation.

Clay soils can especially benefit from the use of gypsum amendments. Clay flocculation, is where the electric double layer is sufficiently compressed so that attractive forces allow coagulation of the individual clay particles into microaggregates (Chen and Dick, 2011), and when the attactive force is disrutped, dispersion occurs. Gypsum amendments to clay soils have been shown to increase water infiltration rates (Baumhardt et al., 1992; Norton et al., 1993), increase subsoil root activity (Radcliffe et al., 1986; Shainberg et al., 1989), and decrease soil loss from dispersive soils (Ben-Hur et al., 1992). In addition, gypsum amendments to clay soils can also reduce surface sealing and erosion of smectitic soil types through flocculation (Norton et al., 1993).

The calcium contained in gypsum can also be used to reduce soluble phosphorus (P) losses in surface water runoff, a concern with agricultural lands fertilized with surface-applied manures such as poultry litter. Excess P runoff can cause eutrophication and algal blooms affecting off-site water quality, as well as aquatic life (Correll, 1998). One of the mechanisms for reduction of P loss is decreasing desegregation of soil particles, reducing the amount of P carried along with sediment losses (McCray and Sumner, 1990). P losses can be reduced by the formation of relatively insoluble Ca-phosphate complexes when Ca in gypsum reacts with soluble phosphate (Brauer et al., 2005). Co-applying gypsum with poultry litter to no-till soil could reduce the amount of soluble reactive P, total P, and total N when applied to normally fertilized fields (Norton, 2008). Other studies also show that application of gypsum to grass buffer strips could reduce soluble P losses from poultry litter applications in concentrated runoff flows under field conditions (Watts and Torbert, 2009), and gypsum applied as a land application on coastal plain soils could reduce soluble P losses to the environment (Torbert and Watts, 2014).

The Role of Sulfur in Plants

Coal combustion from electricity generating plants has increased SO_2 output into the atmosphere, though the SO_2 is quickly converted into a form that can be taken up by plants, SO_4^{2-}. With mandates for coal-fired power plants to combat flue gas output pollutants, along with highly concentrated fertilizers containing little or no S (Scherer, 2001), soil concentrations in sulfur has decreased (Fig. 2), resulting in an increases in deficiencies of S in crops worldwide (Chibber, 2007).

S is an essential element for plant growth and must be available in relatively large amounts for plant metabolism to function properly. Sulfur is a major component of the amino acids cysteine and methionine which are the building blocks of many proteins (Mengel and Kirkby, 1987). Cysteine and methionine are also precursors of other sulfur-containing compounds such as coenzymes and secondary plant products. When sulfur is deficient, synthesis of proteins and photosynthetic rates in plants are decreased (Marschner, 1986).

One of the main functions of sulfur in proteins or polypeptides is the formation of disulfide bonds between polypeptide chains. The disulphide bond can serve as a covalent cross linkage between two polypeptide chains or between two points on a single chain, stabilizing the polypeptide structure (Fig. 3) (Mengel and Kirkby, 1987). An essential biochemical function of sulfur is the formation of disulphide bonds which contribute to the conformation of enzymes and proteins (Mengel and Kirkby, 1987). During dehydration, the number of disulphide bonds in proteins increases at the expense of -SH groups, and this shift is associated with protein aggregation and denaturation (Tomati and Galli, 1979). The protection of -SH groups in proteins from the formation of the disulphide bridges is very important for providing cellular resistance to dehydration due to drought, heat, and frost damage (Levitt, 1980).

When sulfur is deficient, protein synthesis is inhibited. A majority of the proteins containing sulfur are located in chloroplasts. Chlorophyll molecules comprise prosthetic groups of the chromoproteid complex, thus in sulfur-deficient plants, chlorophyll content declines (Marschner, 1986), which leads to reduced plant growth (Mengel and Kirkby, 1987).

Another important group of sulfur-containing compounds are the ferredoxins, which are proteins that contain an iron-sulfur cluster. These proteins are integral in the photosynthetic electron transport chain and can reduce various substances such as $NADP^+$, NO_3^-, SO_4^{-2} and heme proteins (Mengel and Kirkby, 1987). In this reaction, the reduced form is the source of reducing power for the reduction of CO_2 in the dark reactions of photosynthesis, and serves as an electron donor in SO_4^{-2} reduction, N_2 reduction, and glutamate synthesis (Mengel and Kirkby, 1987).

The Role of Calcium in Plants

Calcium is used in the plant for many functions, and is a crucial regulator involved with almost every aspect of plant growth and development. Calcium moves slowly by mass flow to plants, and must be constantly in supply at the root and ready to be taken up by the plant in order for plants to have adequate calcium for metabolic functions. Poor supply of Ca^{2+} to fruit and storage organs can result in calcium deficiency in their tissues (Mengel and Kirkby, 1987). Several defects that arise from deficiencies of calcium include: poor root development, leaf necrosis and curling, blossom end rot, bitter pit, fruit cracking, and poor fruit storage and water soaking (Simon, 1978, White and Broadley, 2003). One of the main underlying issues causing symptoms of blossom end rot is the deficiency of Ca^{2+} which causes the loss of cell wall integrity. Calcium is extremely important for maintenance of membrane stability bridging two negatively charged phosphate groups (Mengel and Kirkby, 1987) (Fig. 4).

Calcium levels within plants are usually rather high, mainly resulting from high calcium levels contained within the soil solution and transported to the xylem. The delivery of calcium from the soil solution to the xylem is restricted to the extreme root tip and to regions in which lateral roots are being initiated (Clarkson, 1993; White, 2001), which plays a critical factor when availability of calcium to the plant is limited in the growth and development of the plant or fruit. The calcium flux to the xylem through the apoplastic pathway is influenced markedly by transpiration, which can lead to vagaries in the amount of calcium supplied to the shoot and the development of calcium-related disorders (Marschner, 1986; McLaughlin and Wimmer, 1999).

Blossom end rot (BER) is a major physiological problem often mistaken for a disease by growers. BER is characterized by a necrotic lesion on the distal or blossom end of tomatoes, peppers, and watermelons (Fig. 5). Phenolic acids that are involved with cross-linkages through the formation of quinone bridges form chelates with Ca^{2+} which leads to the binding of strands of wall polysaccharides together (Painter and Neukom, 1968). Without Ca^{2+}, phenolic acids are oxidized, creating a black pigment that is characteristic of blossom end rot (Dekock et al., 1980).

The tissues affected by a lack of calcium in the plant are supplied by the transpiration stream via the xylem which translocates Ca^{2+} directly from the soil solution. When conditions exist that create low xylem sap flow to transport Ca^{2+} such as humid conditions, water stress, or high salt concentrations in the soil solution, BER may occur (Mengel and Kirkby, 1987). These conditions produce oxidative stresses, and the free oxygen radicals and hydrogen peroxide produced in excess have also been shown to cause membrane lipid peroxidation, enhanced membrane leakage, and tissue degradation (Aktas et al., 2003).

In a study by Dekock, et al. (1980), the biochemical activities of tomatoes with BER were observed to have substantial differences between phenolase and catalase activities in healthy and BER-affected fruit. Phenolase activity was absent in healthy fruit but present in the fruit affected by BER. Amounts of active protein synthesis still occurring in BER-affected tomatoes were considerably less than in healthy fruit, possibly implying that enzymatic activity measured could be from past protein synthesis when the BER tissue was more active. The study also observed that protein-bound hydroxyproline was considerably increased in the tissues affected with BER (Dekock, et al., 1980).

Calcium is also involved in many other aspects of cell function. One of the most important structures is calmodulin (CaM). Calmodulin is a polypeptide consisting of 148 amino acids, is heat stable, insensitive to pH changes, and is bound to 4 Ca^{2+} ions by a change of conformation displacing a hydrophobic section of the polypeptide chain (Fig. 6). The role of calmodulin in plants is to regulate the activity of enzymes, activation of cyclic nucleotide phosphodiesterase, adenylate cyclase, membrane bound Ca^{2+} -ATPase, and NAD-kinase (Mengel and Kirkby, 1987).

Because of increased availability, interest in developing uses for FGD gypsum as a soil amendment in agriculture has increased. However, limited research is available to document the effects of FGD gypsum on plants and soils. The physiological effects of the two elements that make up gypsum, Ca and S, have been well documented throughout the years. However, studies are needed on these combined elements in the form of FGD gypsum to determine whether or not there is a positive effect when used by greenhouse and nursery growers to improve their crops, and provide a source of required nutrients to the plant while eliminating a waste by-product of the power industry.

Literature Cited

Adams, J.F., Hartzog, D.L., and Nelson, D.B. 1993. Supplemental calcium application on yield, grade, and seed quality of runner peanut. Agron J., 85:86-93.

Aktas, H., L. Karni, B. Aloni, and A. Bar-Tal. 2003. Physiological and biochemical mechanisms leading to blossom-end rot in greenhouse-grown peppers, irrigated with saline solution. Acta Hort. 609:81-88.

American Coal Ash Association (ACAA). 2014. 2014 Coal Combustion Product (CCP) Production & Use Survery Report. https://www.acaa-usa.org/Portals/9/Files/PDFs/2014ReportFinal.pdf (accessed 5 July 2016).

Baumhardt, R.L., C.W. Wendt, and J. Moore. 1992. Infiltration in response to water quality, tillage, and gypsum. Soil Sci. Soc. Amer. 56:261-266.

Ben-Hur, M., I. Shainberg, R. Stern, and A.J. van der Merwe. 1992. Slope and gypsum effects on infiltration and erodibility of dispersive and nondispersive soils. Soil Sci. Soc. Amer. J. 56:1571-1576.

Brauer, D., G.E. Aiken, D.H. Pote, S.J. Livingston, L.D. Norton, T.R. Way, and J.H. Edwards. 2005. Amendment effects on soil test phosphorus. J. Environ. Qual. 34:1682-1686.

Chen, L. and W.A. Dick. 2011. Gypsum as an agricultural amendment: General use guidelines. Ohio State University Extension.

Chen, L., W.A. Dick, and S. Nelson. 2005. Flue gas desulfurization products as sulfur sources for alfalfa and soybean. Agron. J. 97:265-271.

Chibber, N. 2007. Sulfur deficiency in Madhya Pradesh soil leads to poor harvest. Down to Earth (15 Aug. 2007). http://www.downtoearth.org.in/news/sulfur-deficiency-in-madhya-pradesh-soil-leads-to-poor-harvest-6346 (accessed 16 July 2015).

Clarkson, D.T. 1993. Roots and the delivery of solutes to the xylem. Physiol. Transactions of the Royal Soc. of London Series B. 341:5-17.

Correll, D.L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual. 27:261-266.

Crocker, W. 1922. History of the use of gypsum. Gypsum Industries Association, Chicago, IL.

Dekock, P.C., D. Vaughan, A. Hall, and B.G. Ord. 1980. Biochemical studies on blossom end rot of tomatoes. Physiologia Plantarum 48:312-316.

Dontsova, K, Y.B. Lee, B. K. Slater, and J. M. Bigham. 2005. Ohio State University Extension Fact Sheet ANR-20-05. Gypsum for Agricultural Use in Ohio - Sources and Quality of Available Products.

Duke Energy. 2017. Sulfur Dioxide Scrubbers. https://www.duke-energy.com/our-company/environment/air-quality/sulfur-dioxide-scrubbers. Accessed December 2017.

Farina, M.P.W., and P. Channon. 1998. Acid-subsoil amelioration: II. Gypsum effects on growth and subsoil chemical properties. Soil Sci. Soc. Amer. 52:175-180.

Levitt, J. 1980. Responses of Plants to Environmental Stresses. 2nd ed., Vol. 2. Academic Press.

Marschner, H. 1986. Marschner's mineral nutrition of higher plants. Academic Press.

McCray, J.M., and M. E. Sumner. 1990. Assessing and modifying Ca and Al levels in acid subsoils. Advances in Soil Sci. Springer New York 45-75.

McLaughlin, S.B. and R. Wimmer. 1999. Calcium physiology and terrestrial ecosystem processes. New Phytologist 142:373-417.

Menge, J. A., H.D. Ohr, E.L.V. Johnson, S. Campbell, F. Guillemet, N. Grech, and E. Pond. 1994. The effect of mulches, gypsum and fungicides on the performance of avocado planted in soil with *Phytophthora cinnamomi* and *P. citricola*. Phytopathology 84:1103.

Mengel, K., and E. Kirkby. 1987. Principles of Plant Nutrition. No. Ed. 4. International Potash Institute.

Miyamoto, S., R.J. Prather, and J.L. Stroehlein. 1975. Sulfuric acid and leaching requirements for reclaiming sodium-affected calcareous soils. Plant and Soil 43:573-585.

National Atmospheric Deposition Program. 2015. http://nadp.sws.uiuc.edu/data/animaps.aspx (accessed 15 July 2015).

Nemec, S. and O. Lee. 1995. Management of phytophthora root rot and blight of citrus with soil amendments. Phytopathology 85:1200.

Norton, L.D. 2008. Gypsum soil amendment as a management practice in conservation tillage to improve water quality. J. of Soil and Water Conservation 63:46A.

Norton, L.D. 2009. Properties of FGD Gypsum that Provides Value for Agricultural Land Application. Retrieved from: http://www.fgdproducts.org/Presentations_Indy_11.../Tue_1410_Norton.pdf (accessed July 2013).

Norton, L.D., I. Shainberg, and K.W. King. 1993. Utilization of gypsiferous amendments to reduce surface sealing in some humid soils of the eastern USA. Catena Supplement 24:77-92.

Oster, J.D., and H. Frenkel. 1980. The chemistry of the reclamation of sodic soils with gypsum and lime. Soil Sci. Soc of America 44:41-45.

Painter, T.J., and H. Neukom. 1968. The mechanism of oxidation gelation of a glycoprotein from wheat flour: Evidence from a model system based upon caffeic acid. Biochimica et Biophysica Acta (BBA)-General Subjects 158:363-381.

Popp, D. 2003. Pollution control innovations and the Clean Air Act of 1990. J. Pol. Anal. Manage 22:641–660.

Radcliffe, D.E., R.L. Clark, and M.E. Sumner. 1986. Effect of gypsum and deep-rooting perennials on subsoil mechanical impedance. Soil Sci. Soc. of America 50:1566-1570.

Scott, W.D., B.D. McCraw, J.E. Motes, and Smith, M. W. 1993. Application of calcium to soil and cultivar affect elemental concentration of watermelon leaf and rind tissue. J. Amer. Soc. Hort. Sci. 118:201-206.

Scherer, H.W. 2001. Sulfur in crop production—invited paper. European J. of Agron. 14:81-111.

Shainberg, I., and J. Letey. 1984. Response of soils to sodic and saline conditions. University of California, Division of Agriculture and Natural Resources.

Shainberg, I., M.E. Sumner, W.P. Miller, M.P.W. Farina, M.A. Pavan, M.V. Fey. (1989). Use of gypsum on soils: a review. Advances in Soil Sci. 9:1-111.

Simon, E.W. 1978. Symptoms of calcium deficiency in plants. New Phytol. 80:1-15.

Snyder, R. 1992. Greenhouse Tomato Handbook. Publication-Cooperative Extension Service, Mississippi State University.

Sumner, M.E. 1993. Sodic soils-New perspectives. Soil Res. 31:683-750.

Toma, M., M.E. Sumner, G. Weeks, and M. Saigusa. 1999. Long-term effects of gypsum on crop yield and subsoil chemical properties. Soil Sci. Soc. of Amer. 63:891-895.

Tomati, U. and Galli, E. 1979. Water stress and -SH-dependent physiological activities in young maize plants. J. of Exp. Botany. 30, 557-563.

Torbert, H.A., and D.B. Watts. 2014. Impact of flue gas desulfurization gypsum application on water quality in a Coastal Plain soil. J. of Environ. Qual. 43:273-280.

USEPA. 2008. Agricultural Uses for Flue Gas Desulfurization (FGD) Gypsum. Retrieved from: http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1001II9.txt (accessed: 16 July 2015).

USEPA. 2017. Annual Wet Deposition. Retrieved from https://www3.epa.gov/castnet/maps/prismdep.html.

USEPA. Coal Ash Basics. 2015. http://www2.epa.gov/coalash/coal-ash-basics (accessed 5 July 2016).

United States Geological Survey (USGS). 2013. Mineral Commodity Summaries. http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/mcs-2013-gypsu.pdf (accessed 16 July 2015).

United States Geological Survey (USGS). 2015. U.S. Geological Survey Minerals Yearbook. https://minerals.usgs.gov/minerals/pubs/commodity/gypsum/myb1-2015-gypsu.pdf (accessed 1 December 2017).

United States Geological Survey (USGS). 2017. Mineral Commodity Summaries, January 2017.
https://minerals.usgs.gov/minerals/pubs/commodity/gypsum/mcs-2017-gypsu.pdf (accessed 1 December, 2017).

United States Energy Information Administration. 2017. Annual Coal Report 2017. https://www.eia.gov/coal/annual/pdf/acr.pdf. (accessed 21 November 2017).

U.S. Salinity Laboratory. 1954. Diagnosis and improvement of saline and alkali soils. USDA Handbook. 60. U.S. Gov. Print. Office, Washington, DC.

Watts, D.B. and H.A. Torbert. 2009. Impact of gypsum applied to grass buffer strips on reducing soluble P in surface water runoff. J. of Environ. Qual. 38:1511-1517.

Wendell, R.R. and K.D. Ritchey. 1996. High-calcium flue gas desulfurization products reduce aluminum toxicity in an Appalachian Soil. J. Environ. Qual. 25:1401-1410.

White, P.J. and M.R. Broadley. 2003. Calcium in plants. Ann. Bot. (Lond.) 92:487-511.

White, P.J. 2001. The pathways of calcium movement to the xylem. J. Exp. Bot. 52: 891-899.

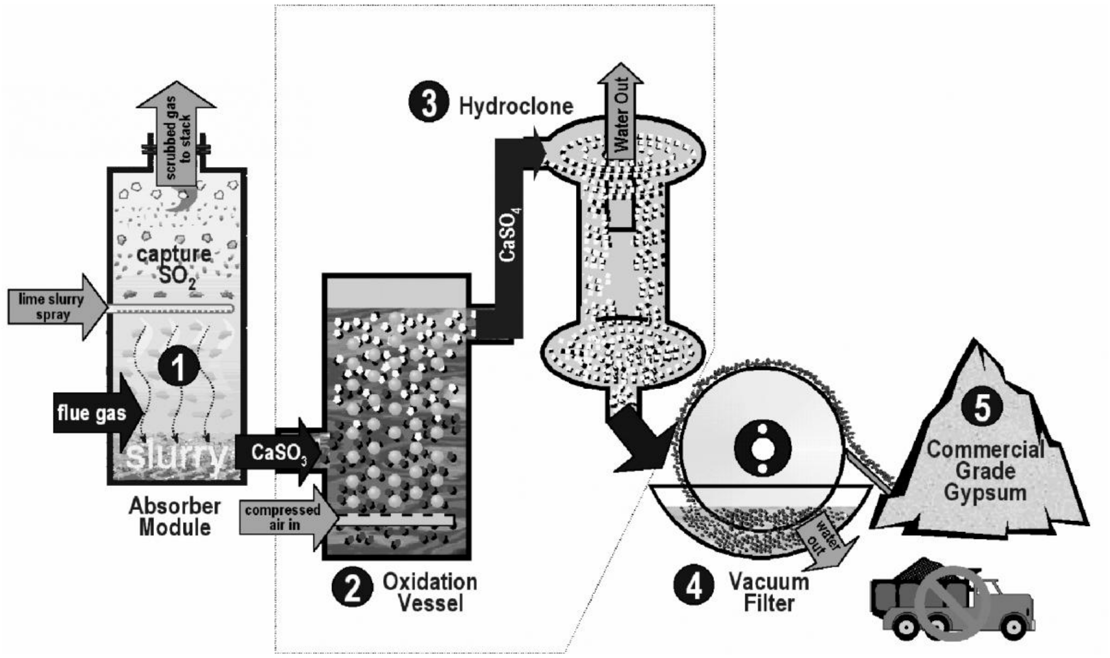
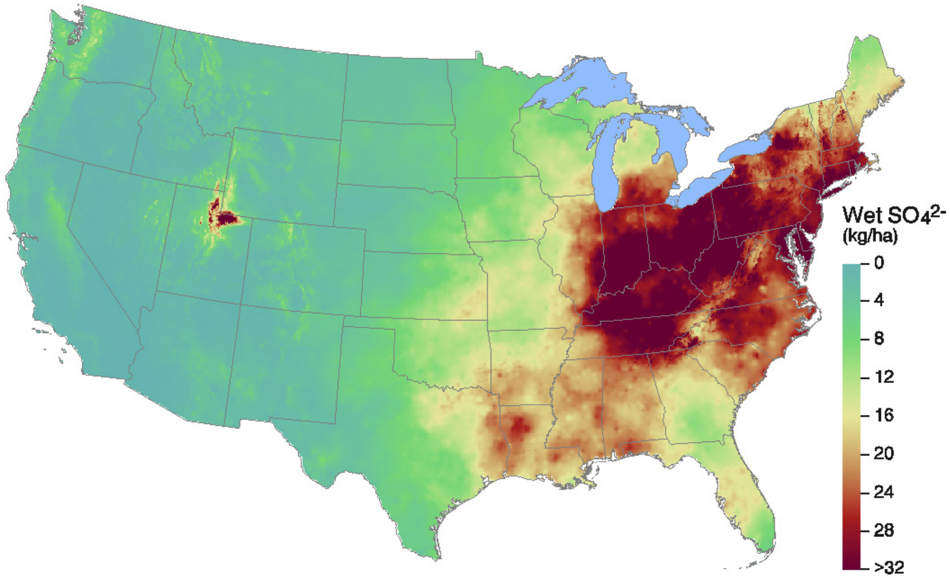


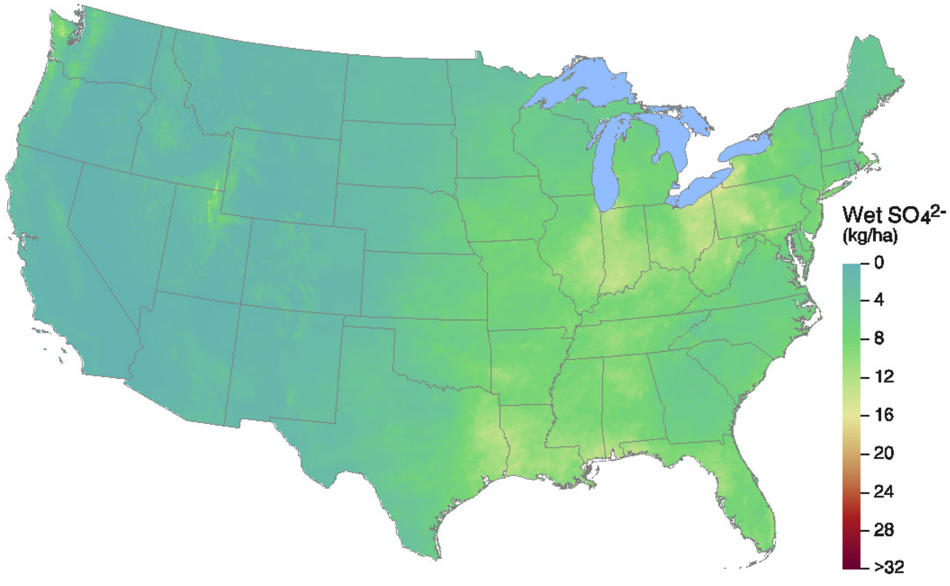
Fig. 1. Graphical representation of a typical scrubber system used in coal-fired power plants that output FGD gypsum. (Figure courtesy of CINERGY Corp., Dontsova, et al. 2005.)



Source: NADP/NTN & PRISM

USEPA/CAMD 05/17/11

/data/arc/prism/gif/1989/so4_d-1989



Source: NADP/NTN & PRISM

USEPA/CAMD 03/03/16

/data/arc/prism/png/1214/so4_d-1214

Fig. 2. The amount of sulfate deposited on the land in rainfall. Red indicates high deposition and green low deposition. Top figure is deposition in 1989, Bottom figure deposition in 2012-2014 (USEPA, 2017).

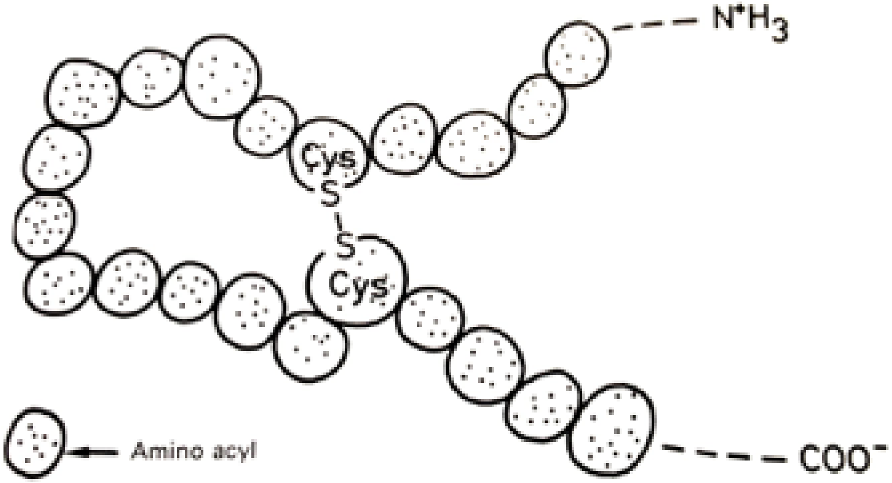


Fig. 3. S-S bridge of a polypeptide chain (Mengel and Kirkby, 1987).

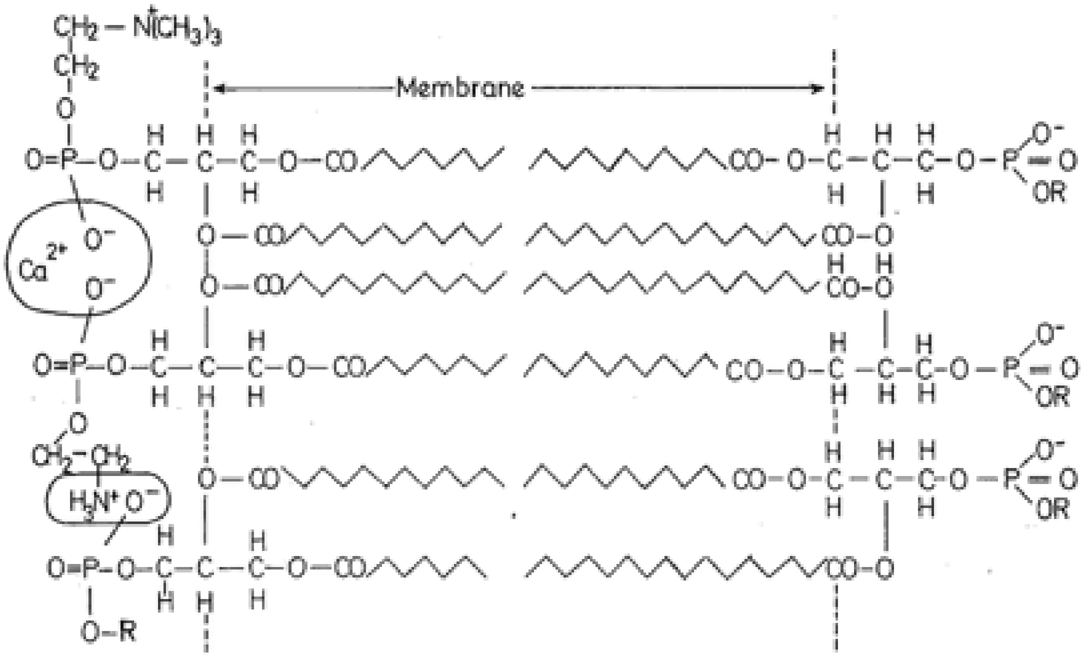


Fig. 4. Schematic representation of a membrane bilayer binding of the two negatively charged phosphate groups (Mengel and Kirkby, 1987).

Fig. 5. Tomatoes unaffected (left) and tomatoes affected (right) with blossom end rot (B. Brown, 2011).

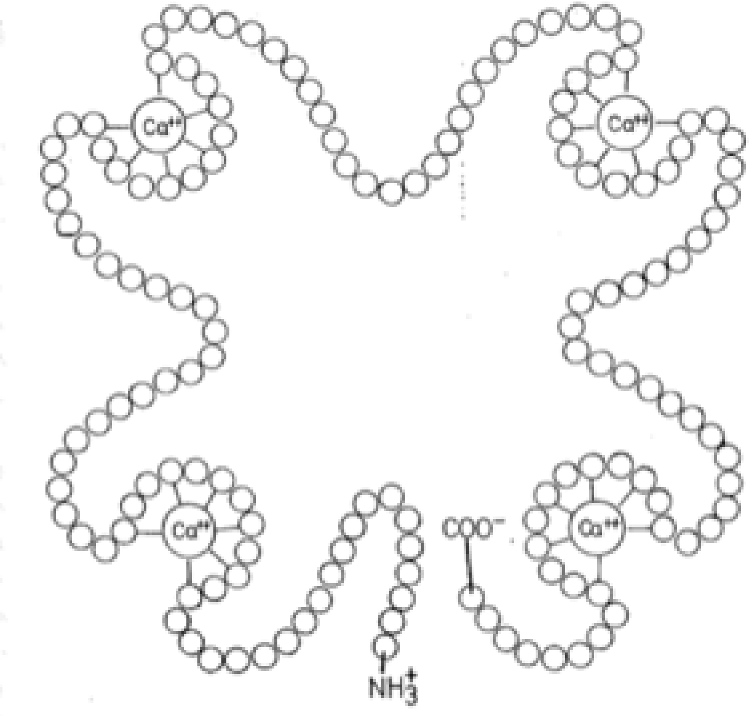


Fig. 6. The calmodoulin structure consists of a 148 amino acid chain bound to four Ca^{2+} ions by conformational change (Mengel and Kirkby, 1987).

Chapter II

Influence of Gypsum on Container-Grown Tomato and Incidence of Blossom End Rot

Abstract. Blossom end rot (BER) is often an issue when growing tomatoes (*Solanum lycopersicum* L.) or other Solanaceae plants due to a lack of calcium in the actively growing blossom end of fruit. Often dolomitic lime, or $CaCO_3$ is used to provide calcium to the plants as a substrate amendment. Flue gas desulfurization (FGD) gypsum, or synthetic gypsum, obtained from coal-fired power producing facilities, can be a source of calcium for plant crops that are susceptible to BER. FGD gypsum was incorporated as an amendment to substrates of greenhouse grown tomatoes to determine if the occurrence of BER would be reduced with increasing rates. The treatments included a control treatment with no FGD gypsum, along with FGD gypsum incorporated into the substrate at the rate of 3.26 $kg \cdot m^{-3}$ (5.5 lbs/yd^3). The rate of 3.26 kg/m^3 is the calcium equivalent of 3.0 $kg \cdot m^{-3}$ (5 lbs/yd^3) of dolomitic lime (DL). Successive treatments of 6.52, 9.78, 13.0, and 16.3 $kg \cdot m^{-3}$ (11, 16.5, 22 and 27.5 lbs/yd^3, respectively) preplant incorporated in the substrate were also evaluated. In the first experiment BER occurred in all treatments, though the lowest occurrence of BER observed on the no-FGD gypsum treatment plants supplied with a commercial fertilizer treatment containing no Ca. Fruit number was variable across treatments and several treatments were similar. The lowest fruit number occurred in the control treatment. Fruit weight means were similar due to high variability across treatments. In the second experiment, no BER occurred regardless of treatment. Differences in mean fruit number between the control (no gypsum added) and the FGD gypsum treatments were also present. The control treatment also had the lowest mean fruit number. Fruit weight was similar to fruit number with the control having the lowest mean weight. There were differences in the control versus the other treatments, as all the incorporated gypsum treatments were similar. Results suggest that having an available source of calcium as with incorporation of FGD gypsum would alleviate one of the factors that cause BER on tomatoes and could serve as a preventative treatment practice by providing an available source of Ca when Ca is the limiting factor.

Introduction

Field grown tomatoes (*Solanum lycopersicum* L.) have been the standard source of tomatoes from World War II until the mid 1990's (DeGiglio, 2003). However, in North America, container-grown greenhouse tomatoes now represent 17 percent of the North American fresh tomato supply (Cook and Calvin, 2005). The catalyst fueling this dramatic growth is consumer perception that greenhouse tomatoes are superior in their consistent quality and taste compared to the standard field grown artificially ripened tomatoes (DeGiglio, 2003). Producers of container-grown tomatoes face numerous management issues, including one of the most detrimental, blossom end rot (BER). Blossom end rot is a physiological condition often mistaken for a disease by novice growers, yet the true underlying cause of BER has been known for years. Crop loss due to BER can vary greatly from trace losses to fifty percent or greater loss. The accepted cause of BER has been reduced availability of calcium (Ca^{2+}) to the tomato. Calcium is one of the most important elements needed for plant growth and development of tomatoes and other Solanaceae crops. Several defects arising from calcium deficiencies include: poor root development, leaf necrosis and curling, BER, bitter pit, fruit cracking, poor fruit storage and water soaking (Simon, 1978; White and Broadley, 2003). The tissues affected by the lack of calcium in the plant are sustained by the transpiration stream via the xylem which translocates Ca^{2+} directly from the soil solution. When conditions exist that create low xylem sap to transport Ca^{2+} such as humid conditions, water stress, or high salt concentrations in the soil solution, BER may occur (Mengel and Kirkby, 1987).

One way Ca can be provided to plants is through the use of gypsum. Gypsum (calcium sulfate dihydrate ($CaSO_4 \cdot 2\ H_2O$) is a naturally occurring colorless and odorless very fine textured solid mineral, with a particle size typically finer than 50 µm (Norton, 2009). Gypsum has been used for hundreds of years and was one of the earliest nutrient sources for plants and soil conditioner dating back to the late 18th century (Crocker, 1922). Gypsum has been shown to improve overall plant growth, improve soil physical and chemical properties, aid in sodic soil reclamation, and supplies the essential plant nutrients calcium and sulfur (Chen and Dick, 2011). Gypsum is usually mined from natural deposits in the earth, but can also be produced through flue gas desulfurization (FGD) emissions controls, also known as “scrubbers”, that capture sulfur dioxide (SO_2) emissions from the burning of high sulfur-containing coal. In 2016, the mined form of gypsum accounted for an estimated 11.5 million tons in the United States, and the synthetic form accounted for an estimated 11.5 million tons (USGS, 2016). These scrubbers are used to eliminate the contaminants which would otherwise enter the atmosphere and cause detrimental effects to the environment. The gypsum produced through the scrubbing process is referred to as flue gas desulfurization (FGD) gypsum. Because FGD gypsum is comparable to mined gypsum, there is a significant potential for greater application and use in agricultural settings, specifically horticultural use, yet only about 4% percent of the FGD gypsum produced is being used for agriculture (ACAA, 2014). Because of increased availability, interest in developing uses for FGD gypsum as a soil amendment in agriculture has increased. However, limited research has documented the effects of FGD gypsum on horticultural greenhouse and nursery crops. This study focused on the effect of incorporating FGD gypsum into a soilless substrate during the production of greenhouse-grown tomatoes.

Materials and Methods

This study took place in the fall of 2011 in the Auburn University Aquaponics Research Greenhouses located at the North Auburn Fisheries Station in Auburn, Alabama (32.650056, -85.486838) for duration of five months beginning in August of 2011 and terminating January 2012. The study was repeated in 2013 at the Ornamental Horticulture Research Center greenhouses in Mobile, Alabama (30.702305, -88.145643) following the same procedures as in 2011, with the exception of termination in April 2014. The FGD gypsum used was sourced from Big Bend Power Station, part of Tampa Electrical Cooperative (TECO) located in Tampa, Florida.

In both experiments, ‘Geronimo’ tomatoes (*Solanum lycopersicum* ‘Geronimo’), a type of greenhouse-grown tomato, were transplanted from seedlings grown at the Auburn University Aquaponics Research Greenhouses into a 6:1 pinebark:sand substrate. Plants were transplanted from plugs to three gallon nursery pots. There were seven total treatments in the study, including a control with no FGD gypsum, incorporated into the soilless substrate using a cement mixer. Each treatment included seven replications in a completely random experimental design. The treatments included a control treatment of no FGD gypsum, along with FGD gypsum incorporated into the substrate at the rate of 3.26 kg • m^{-3} (5.5 lbs/yd^3), (the rate of 3.26 kg • m^{-3} is the calcium equivalent of 3.0 kg/m^3 (5 lbs/yd^3) of dolomitic lime (DL)), and successive treatments of 6.52, 9.78, 13.0, and 16.3 kg • m^{-3} (11, 16.5, 22 and 27.5 lbs/yd^3, respectively) preplant incorporated into substrate mixes. All FGD gypsum was sieved with a #14 mesh screen (1.4 mm, 0.0555 in.) before incorporation into the substrate to eliminate large chunks of the FGD gypsum. The final treatment was an application of a bag culture tomato special fertilizer (Snyder, 2016) mixed to the specific nutrient specifications as a commercially available fertilizer of 3-19-29 (TotalGro, STD Industries, Inc.) with 110 ppm N through the addition of $CaNO_3$ (Table 2.1). The commercial fertilizer treatment was used to determine what effect applied liquid fertilizer containing Ca would have in relation to the gypsum treatments. The other six treatments were fertilized with the same bag tomato special, but was absent of the $CaNO_3$ to partition the availability of calcium only from the gypsum. All fertilization was applied through a Dosatron Injector (Model D14MZ2VFII, Dosatron USA, Clearwater, FL) at a 128:1 ratio. Tomatoes for the first experiement were harvested as fruit matured and became fully red by USDA standards for tomatoes (USDA, 1997) beginning December 2011, and the second experiement tomatoes were harvested beginning in December 2013. Data collected included the occurrence of BER, fruit yield, and fruit weight for each treatment. Analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). Where residual plots and a significant COVTEST statement using the HOMOGENEITY option indicated heterogeneous variance, a RANDOM statement with the GROUP option was used to correct heterogeneity. Regression analysis was then performed in PROC GLIMMIX to determine linear or quadratic trends with increasing gypsum concentration. In the cases of significant quadratic trends, predicted values and 95% confidence intervals were calculated to determine the gypsum concentration yielding a maximum response. Statistics in the second experiment used a negative binomial distribution. All reported means are least squares means. Statistical differences were determined at $\alpha=0.05$.

Results and Discussion

In the first experiment conducted at the North Auburn Fisheries Station, BER was observed across all treatments with no discernable increasing or decreasing pattern (Table 2). Similarities existed between the control at 0, 9.78, 13.0, and 16.3 kg • m^{-3} (0 lbs/yd^3, 16.5 lbs/yd^3, 22 lbs.yd^3, 27.5 lbs/yd^3), and the commercial fertilizer treatments. However, the lowest occurrence of BER was in the treatment using the commercial fertilizer containing no FGD gypsum, though statistically similar to the control. There was no significant regression for BER occurrence in the tomatoes. Fruit number was also variable across all treatments. The lowest number of fruit occurred in the control, and was similar to 6.52 kg • m^{-3} and the commerical fertilizer treatment. Fruit weight means were statistically the same across all treatments as compared to the control, though high variability was observed across all treatments, including the control.

The second experiment conducted at the Ornamental Research Station in Mobile, AL was a repeat of the first. Blossom end rot was not observed across any of the treatments (Table 3). Mean fruit number of treatments of FGD gypsum was higher than the control. Fruit weight was similar to fruit number in that the control had the lowest mean weight, and all FGD gypsum treatments had much higher weights versus the control, and was highest at 9.78 kg • m^{-3}.

Typically the calcium source used in most greenhouse and nursery grown plants is dolomitic lime. Lime can provide a pH adjustment as well, however, gypsum can be used as a viable alternative if a growth media's pH level is optimal. Greenhouse tomato growers that grow in-ground can incorporate lime or gypsum to supplement Ca to the crop, however many growers use fertigation to supplement their plants with $CaCO_3$. FGD gypsum could be considered an alternative Ca source to $CaCO_3$ fertigation due to the higher solubility of gypsum. In these experiments, the first study had a shorter duration, while the second experiment was conducted for a slightly longer duration and had more consistent fruit number and fruit weight across all treatments. It is possible that the inconsistency of the results in BER and fruit number of the first experiment was due to the shortening day length, or other environmental factors not recorded during the experiment. In the second experiment, there was no occurrence of blossom end rot, however, fruit number and fruit weights were different from the control treatment (Table 3).

BER has been suspected to not only be due to a lack of Ca issue, but also due to many other environmental factors such as: interactions between daily irradiance, air temperature, water availability, salinity, nutrient ratios in the rhizosphere, root temperature air humidity and xylem tissue development in the fruit all contribute to BER incidence (Dorais and Papadopoulos, 2001; Adams and Ho, 1993; Ho et. al, 1993). Many studies have been conducted over the years to attempt to describe the actual causes of BER, but due to the inherent variability in causation of the disorder, there can be no single conclusive cause of BER. There is also reason to suspect that water availability could be the limiting factor in prevention of BER. Due to Ca being a non-mobile nutrient within the plant, movement depends on mass flow to translocate throughout the plant. If plants are subjected to water stress due to drought or environmental changes, such as high humidity or lower temperatures that can lead to decreased transpiration, Ca will not be available to the actively growing areas of the fruit, thus preventing the fruit from forming correcetly and causing BER. This is critical during the early developmental stages of the tomato fruit. Having an available source of calcium as with incorporation of FGD gypsum would alleviate one of the factors that cause BER on tomatoes or other Solanaceae crops and could serve as a preventative treatment practice by providing an available source of Ca when Ca is the limiting factor, thus preventing losses of tomato crops due to BER that can be devastating to tomato crops.

Literature Cited

Adams, P. and L.C. Ho. 1993. Effects of environment on the uptake and distribution of calcium in tomato and on the incidence of blossom-end rot. Plant Soil 154:127-132.

American Coal Ash Association (ACAA). 2014. 2014 Coal Combustion Product (CCP) Production & Use Survery Report. https://www.acaa-usa.org/Portals/9/Files/PDFs/2014ReportFinal.pdf (accessed 5 July 2016).

Cook, R.L. and L. Calvin. 2005. Greenhouse tomatoes change the dynamics of the North American fresh tomato industry (No. 3). U.S. Department of Agriculture, Economic Research Service.

Chen, L. and W.A. Dick. 2011. Gypsum as an agricultural amendment: General use guidelines. Ohio State University Extension.

Crocker, W. 1922. History of the use of gypsum. Gypsum Industries Association, Chicago, IL.

DeGiglio, M.A. 2003. Growth of the fresh greenhouse tomato market in the USA. Acta Hort. 611:91-92.

Dorais, M., A.P. Papadopoulos and A. Gosselin. 2001. Influence of electric conductivity management on greenhouse tomato yield and fruit quality. Agronomie 21:367-383.

Ho, L.C., R. Belda, M. Brown, J. Andrews, and P. Adams. 1993. Uptake and transport of calcium and the possible causes of blossom-end rot in tomato. J. Exp. Bot. 44:509–518.

Jones, B. 2004. Hydroponics: A Practical Guide for the Soilless Grower, Second Edition. CRC Press. Page 82.

Mengel, K. and E. Kirkby. 1987. Principles of Plant Nutrition. No. Ed. 4. International Potash Institute.

Norton, L. D. 2009. Properties of FGD Gypsum that Provides Value for Agricultural Land Application. Retrieved from: http://www.fgdproducts.org/Presentations_Indy_11.../Tue_1410_Norton.pdf. (last accessed Aug 2015).

The data analysis for this paper was generated using SAS software, Version 9.2 of the SAS System for Unix. Copyright © 2012 SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA.

Simon, E.W. 1978. The symptoms of calcium deficiency in plants. New Phytologist, 80:1-15.

Snyder, R.G. 2016. Greenhouse Tomato Handbook. Mississippi State University. Mississippi State University Extension Service. Publication 1828. Retrieved from: http://msucares.com/pubs/pub1828.htm.

United States Department of Agriculture. 1997. United States Standards for Grades of Fresh Tomatoes.

United States Geological Survey. 2016. Mineral Commodity Summaries. http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/mcs-2016-gypsu.pdf (accessed 6 July 2016).

White, P. J., and M.R. Broadley. 2003. Calcium in plants. Annals of Bot. 92:487-511.

Table 1. Hydroponic Fertilizer (mimics Total Gro 3-13-29 but without calcium and a large percentage of sulfur).

		Stock Tank* (l)	**Pre injector****	**Final Conc. per stock tank**	**Max Solubility *****	**soluble check**
Reagent	**mg/L**		**mg/tank**			
MKP	219	18.9	4144.6	530.5	330	✓
KNO_3	468.4	18.9	8864.5	1134.7	133	✓
$MgNO_3$	416.5	18.9	7882.3	1008.9	1250	✓
$MgSO_4$	146	18.9	2763.1	353.7	1053	✓
138 Sequestrene 138 Fe	54.6	18.9	1033.3	132.3	60	✓
Max Manganese	20	18.9	378.5	48.4	-	✓
Copper sulfate	4	18.9	75.7	9.7	316	✓
Zinc Sulfate	1.27	18.9	24.0	3.1	965	✓
Borax	8.84	18.9	167.3	21.4	20.1	✓
Molybdenum sulfate	0.25	18.9	4.7	0.6	443	✓
				3243.3		

*Tank = 5 gallon (18.9271 liter) bucket stock tank.

**Pre-injector = concentration before increase due to injector ratio (1:128).

***Jones. 2004. Hydroponics: A Practical Guide for the Soilless Grower, Second Edition. CRC Press. Page 82.

Table 2. Effects of increasing rates of FGD gypsum on tomato - North Auburn Fisheries Complex.

FGD gypsum	BER[zy]	Fruit Number[y]	Fruit Weight[xy]
0 kg/m^3 (0 lbs/yd^3)	0.21 c	17.93 c	42.43 a
3.26 kg/m^3 (5.5 lbs/yd^3)	2.29 ab	21.79 ab	13.07 a
6.52 kg/m^3 (11 lbs/yd^3)	3.00 a	20.00 bc	37.86 a
9.78 kg/m^3 (16.5 lbs/yd^3)	0.71 abc	21.29 ab	19.64 a
13.0 kg/m^3 (22 lbs/yd^3)	0.29 bc	23.29 a	31.86 a
16.3 kg/m^3 (27.5 lbs/yd^3)	1.14 abc	21.29 ab	9.14 a
Commercial fertilizer treatment[w]	0.07 c	20.86 bc	16.43 a
Significance	NS*	Q*	Q*

[z] Blossom End Rot, number of fruit with BER ($P \leq 0.05$).

[y] Column means within treatment are not significantly different when followed by the same letter ($P \leq 0.05$).

[x] Fruit Weight in grams ($P \leq 0.05$).

[w] Bag special tomato fertilizer with calcium as $CaNO_3$.

*NS = Nonsignificant; L = linear; or Q = quadratic response at $P \leq 0.05$ based on single degree-of-freedom orthogonal contrasts.

Table 3. Effects of increasing rates of FGD gypsum on tomato - Ornamental Research Station, Mobile, AL.

FGD gypsum	BER[zy]	Fruit Number[y]	Fruit Weight[xy]
0 kg/m^3 (0 lbs/yd^3)	-	0.93 b	171.16 b
3.26 kg/m^3 (5.5 lbs/yd^3)	-	2.76 a	331.09 a
6.52 kg/m^3 (11 lbs/yd^3)	-	2.33 a	363.76 a
9.78 kg/m^3 (16.5 lbs/yd^3)	-	2.37 a	422.70 a
13.0 kg/m^3 (22 lbs/yd^3)	-	2.41 a	395.59 a
16.3 kg/m^3 (27.5 lbs/yd^3)	-	2.42 a	400.35 a
Commercial fertilizer treatment[w]	-	2.58 a	420.41 a
Significance	NS*	Q*	Q*

[z] Blossom End Rot, number of fruit with BER ($P \leq 0.05$).

[y] Column means within treatment are not significantly different when followed by the same letter ($P \leq 0.05$).

[x] Fruit Weight in grams ($P \leq 0.05$).

[w] Bag special tomato fertilizer with calcium as CaNO$_3$.

[*] NS = Nonsignificant; L = linear; or Q = quadratic response at $P \leq 0.05$ based on single degree-of-freedom orthogonal contrasts.

Fig. 1. Blossom end rot tomato experiment at the North Auburn Fisheries Station, Auburn, AL (B. Brown, 2011).

Fig. 2. Tomatoes unaffected by blossom end rot (left), and affected by blossom end rot (right) (B. Brown, 2011).

CHAPTER III

Influence of FGD Gypsum on Growth of Three Greenhouse Crops

Abstract. Greenhouse grown ornamental plants often have high calcium requirements in order to produce quality crops. Flue gas desulfurization (FGD) gypsum, a waste product typically from coal-fired power producing facilities could be used as a source of calcium for greenhouse-grown plants. The objective of these studies were to determine the effects of increasing rates of FGD gypsum on three high calcium-requiring greenhouse crops. FGD gypsum amendments were 0, 3.26, 6.52, 9.78, 13.0 kg • m^{-3}, along with treatments of 3 kg • m^{-3} dolomitic limestone, and 3 kg • m^{-3} dolomitic limestone + 3.26 kg • m^{-3} FGD gypsum preplant incorporated into a Fafard 3B substrate with two greenhouse crops: zonal geranium (*Pelargonium* x *hortorum*) and petunia (*Petunia* x *hybrida*). In a second study, FGD gypsum was preplant incorporated at rates of 0, 3.26, 6.52, 9.78, 13.0, 16.3, and 19.58 kg • m^{-3} into a Fafard 3B substrate with three species of fern: *Nephrolepis obliterata*, *N. exaltata* 'Bostoniensis', and *N. exaltata* 'Roosevelt'. Geranium growth index (GI) increased as FGD gypsum levels increased and dry weight increased slightly. Petunia GI decreased as levels of FGD gypsum increased, and no differences were observed for fresh or dry weights. All fern species indicated varying responses for growth index. *N. obliterata* GI increased up to 13.0 kg • m^{-3} FGD gypsum, and decreased at

higher rates. *N. exaltata* 'Bosteniensis' highest GI was observed at 16.3 kg • m^{-3}. *N. exaltata* 'Roosevelt' GI decreased with all treatments as compared to the control. Based on the GI results of this study, geranium greenhouse production may benefit from incorporating FGD gypsum when using a peat:pine bark-based substrate such as Fafard 3B. In petunia production, it is recommended to use a lower rate of 3.26 kg • m^{-3} FGD gypsum, as GI did increase compared to the control rate of 0 kg • m^{-3}. *N. oblierata* and *N. exaltata* 'Bostoniensis' GI increased when compared to the control, and the highest recommended treatment would be 13.0 and 16.3 kg • m^{-3}, respectively. There were no observable detrimental effects to adding additional FGD gypsum, and FGD gypsum may provide an alternative source of calcium when pH does not need correcting.

Introduction

Gypsum (calcium sulfate dihydrate ($CaSO_4 \cdot 2\ H_2O$) is a naturally occurring colorless and odorless very fine textured solid mineral, with a particle size typically finer than 50 µm (Norton, 2009). Gypsum was one of the earliest forms of plant nutrient sources and soil conditioners dating back to the late 18th century (Crocker, 1922). Gypsum has traditionally been mined from natural deposits in the earth, but can also be produced synthetically as a byproduct when burning high sulfur-containing coal, typically from electricity generating power plants. These coal-burning power plants contain what is generally referred to as a scrubber system. A scrubber system is the informal name for flue gas desulfurization (FGD) technology, which removes SO_2 emissions from the exhaust of coal-fired power plants. A scrubber works by spraying a wet slurry of limestone into a large chamber where the calcium in the limestone reacts with the SO_2 in the flue gas. Once sulfur is burned and produces SO_2, the exhaust gas passes through the scrubber where a spray mixture of limestone (or other chemical reagent) and water reacts with the SO_2. The reaction enables the SO_2 to be removed before the SO_2 is released into the atmosphere. When SO_2 combines with the limestone spray mixture, a primary byproduct produced is gypsum, known as flue gas desulfurization (FGD) gypsum that can be utilized for beneficial uses in the same way as mined gypsum (Duke Energy, 2017). Although many other industries utilize the majority of FGD gypsum produced, agriculture utilizes a small percentage of current usage, but offers one of the greatest potentials for increased use of FGD gypsum. Approximately over 770,000 tons of FGD gypsum is used in agriculture, which according to the American Coal Ash Association represents about 4% of all the FGD gypsum produced in the United States (ACAA, 2017).

In mineral soils, gypsum has been shown to improve overall plant growth, improve soil physical and chemical properties, aid in sodic soil reclamation, and supply the essential plant nutrients of Ca and S. The Ca and S contained within FGD gypsum are readily utilized as nutrients in plants due to the solubility of gypsum ($2.5 \text{ g} \cdot \text{L}^{-1}$ at 20ºC) and small and uniform particle size (<150 microns) (Chen and Dick, 2011). Using gypsum as a source for Ca for plant nutrition (Chen et al., 2005) is common throughout the southern United States as a source of Ca for high Ca-requiring crops, such as peanuts. Another benefit of increased Ca was observed where increasing rates of Ca applied to soil reduced the incidence of blossom end rot (BER) in ‘Charleston Gray’ watermelons (Scott et al., 1993). Other studies using gypsum to supply Ca to plants showed significantly increased plant growth, yield, and root growth, as well as reduced *Phythophthora* *citricola* incidence (Menge, et al., 1994). Additionally, Nemec and Lee (1995) observed that gypsum-amended field soil significantly reduced root rot caused by another species of *Phythophthora* in citrus trees. Sulfur supplied by gypsum was shown to be useful in areas where S was depleted due to factors such as use of fertilizers with little or no S content (Scherer, 2001), and less S deposition from the atmosphere (National Atmospheric Deposition Program, 2015). With deficiencies of S increasing worldwide (Chibber, 2007), gypsum could also provide the needed S on deficient soils (Chen et al., 2005).

Ground dolomitic limestone ($CaCO_3/MgCO_3$) is typically used throughout the southeastern United States as a fertilizer amendment to soilless media. One study observed that plants amended with CaO, agricultural gypsum ($CaSO_4 \cdot 2\ H_2O$), or pelletized dolomitic limestone, were of similar or better quality than plants amended with ground dolomitic limestone (Mayfield, 2002). Whole plant nutrient analysis also had the greatest nutrient uptake of N, Ca, K, and P for treatments amended with CaO, agricultural gypsum, or pelletized dolomitic limestone . The study concluded that CaO, CaO/MgO/$CaCO_3$ blends, $CaSO_4 \cdot 2\ H_2O$, or pelletized limestone may serve as suitable alternatives to ground dolomitic limestone for use in soilless media (Mayfield, 2002).

Preplant incorporation of ground limestone is an accepted practice at nurseries all across the United States, and lime is also the main source of fertilizer Ca and Mg for nursery stock (Mayfield, 2002). Soilless substrate chemistry differs from that of mineral soil, and in recent years, research has questioned the need for limestone in soilless substrates. Studies show container-grown plants to grow well at a pH range of 5.0 to 5.5 in organic media (Bunt, 1988; Lucas and Davis 1961), which is much lower compared to pH ranges required for plants growing in mineral soils (pH 5.8-6.8) (Mayfield, 2002).

One of the largest production areas for foliage and tropical plants in the world is located in the Tampa region of Florida. Central and south Florida is also key to the nation's fruit and vegetable supply, both from indoor and outdoor-conventional production systems. Located within close proximity to these greenhouse and nursery production facilities is Tampa Electric Cooperative's Big Bend electricity generating facility that produces approximately 700,000 tons of FGD gypsum product every year (Florida Public Service Commission, 2011). Using FGD gypsum in a greenhouse setting as an added-value product could be of great benefit to the nursery and greenhouse industry while also mitigating FGD gypsum wastes. The FGD gypsum used in these studies was from the Tampa Electric Company (TECO) Big Bend Power Station, located very close to many ornamental horticultural crop production facilities. The objective of these studies were to determine the effects of increasing rates of FGD gypsum on three high calcium-requiring greenhouse crops.

Materials and Methods

Two greenhouse studies were conducted at the Auburn University Department of Horticulture's research facilities in Auburn, AL (32.5934° N, 85.4952° W). The FGD gypsum used was sourced from the Big Bend Power Station, a part of Tampa Electrical Cooperative (TECO) in Tampa, Florida. All FGD gypsum was sieved with a #14 mesh screen (1.4 mm, 0.0555 in.) before incorporation into substrates to obtain a uniform size. In the first study, two species were used: zonal geranium (*Pelargonium* x *hortorum*) and petunia (*Petunia* x *hybrida*). FGD gypsum preplant amendments were 0, 3.26, 6.52, 9.78, 13.0 kg • m^{-3}, 3 kg • m^{-3} dolomitic limestone (DL), and 3 kg • m^{-3} dolomitic limestone + 3.26 kg • m^{-3} FGD gypsum. Treatments intervals of 3.26 kg • m^{-3} were based on the calcium equivalent of 3 kg • m^{-3} of DL. The FGD gypsum was incorporated with a concrete mixer into a Fafard 3B soil mix substrate. Geranium and petunia plugs were transplanted to 1 quart pots. The experiment was a randomized complete block design and each treatment included 15 replications. Plants were hand watered daily as needed, and fertilized weekly with a 20-10-20 liquid fertilizer using a 100:1 Dosatron Injector (Model D14MZ2VFII, Dosatron USA, Clearwater, FL). Before termination, growth indices were measured (height + $width^1$ + $width^2$ /3). Both species were harvested after a growth period of 8 weeks by cutting the entire plant at the base of the main stem. After termination, plants were weighed to obtain fresh weighs and then dried for 48 hours at 170ºF for final dry weight measure. Tissue analysis was performed for each species and each treatment of FGD gypsum by the Auburn University Soil Testing Laboratory and tested for macro and micro nutrients as well as total nitrogen and total sulfur.

In a second study, three cultivars of ferns were evaluated including: *Nephrolepis obliterata*, *N. exaltata* 'Bostoniensis', and *N. exaltata* 'Roosevelt'. The study included treatments with FGD gypsum rates of 0, 3.26, 6.52, 9.78, 13.0, 16.3, and 19.58 kg • m^{-3} preplant incorporated into Fafard 3B growing mix (Sun Gro Horticulture, Agawam, MA). Ferns were transplanted from plugs into 1 quart pots. The experiment was a randomized complete block design and each treatment included 15 replications. The plants were hand watered daily as needed and fertilized weekly with a 16-6-12 liquid fertilizer at 0.9 lbs N/ m^3 using a Dosatron Injector (Model D14MZ2VFII, Dosatron USA, Clearwater, FL) with a 100:1 injector ratio. Data collected were growth indices (height + width^1 + width^2 /3), pH, and electrical conductivity (EC).

An analysis of variance was performed on all responses for both studies using PROC GLIMMIX in SAS version 9.2 (SAS Institute, Cary, NC). Where residual plots and a significant COVTEST statement using the HOMOGENEITY option indicated heterogeneous variance, a RANDOM statement with the GROUP option was used to correct heterogeneity. Regression analysis was then performed in PROC GLIMMIX to determine linear or quadratic trends with increasing FGD gypsum concentration. All reported means are least squares means. All significances were at α=0.05.

Results and Discussion

In the first study, mean differences in geraniums were observed in the fresh weights between treatments of FGD gypsum (Table 1). There was a negative quadratic response in fresh weights as levels of FGD gypsum increased above 5.7 kg • m^{-3}, and continued negative for the treatments of dolomitic lime and lime + gypsum (Fig. 1). Fresh and dry weighs were highest at 9.87 kg • m^{-3}, though dry weights of the geraniums showed no differences in means in the treatments of FGD gypsum (Table 1). Regression of DW was quadratic, increasing slightly as FGD gypsum rate increased and decreased for the DL and gypsum plus lime treatments (Fig. 2). The pH levels of the gypsum treatments at termination ranged from 6.09 to 6.11 with no mean differences in gypsum treatments and dolomitic lime (DL) and gypsum plus DL treatments differing as expected due to the DL raising the pH. pH levels in gypsum treatments of the geraniums had a slightly negative quadratic response (Fig. 3). There were no differences across all treatments that contained gypsum in electrical conductivity (EC) but were different than the control of 0 kg • m^{-3}. Also, the DL and gypsum plus DL treatments were different and means were lower (Table 1). Geranium growth indices had a positive linear response as the rate of FGD gypsum treatment levels increased (Fig. 4). Slight differences were observed between treatment means of the GI, with the maximum treatment of FGD gypsum at 13 kg • m^{-3} having the highest GI. Growth indices for the lime and gypsum plus lime treatments were similar to the 13 kg • m^{-3} treatment (Table 1).

Petunia fresh weights indicated no difference in means among treatments of FGD gypsum (Table 2). Dry weights indicated similarities between all treatments, with no differences between the control, the treatment of 3.26 kg • m^{-3}, and gypsum plus lime treatments. Regression analysis was not significant for DW. Petunia growth indices were different among all treatments of FGD gypsum and decreased from the maximum GI of 32.1cm at the lowest treatment level of 3.26 kg • m^{-3} FGD gypsum, and decreased as the treatment level of FGD gypsum increased for each treatment. The treatments of DL and DL+gypsum were also different from the control and decreased GI. There were no differences in the control versus the treatments containing DL, nor with the lowest level of FGD gypsum. The regression analysis was negatively quadratic (Fig. 5). Means of EC levels were much higher for treatments of FGD gypsum as compared to the control. The DL treatments showed significantly decreased EC as compared to the control and to treatments containing gypsum (Fig. 6).

In the second study, the three species of ferns had various results across each cultivar. Analysis of *N. obliterata* (Australian sword fern) species indicated a cubic response with a maximum growth index of 18.2 cm at treatment level of 7.86 kg • m^{-3} of FGD gypsum, decreasing with increasing levels of applied gypsum (Fig. 7). Means were similar with the exception of the highest rate of 19.58 kg • m^{-3}, which was lower (Table 3) but similar to the 16.3 kg • m^{-3} treatment. With *N. exaltata* 'Bostoniensis', differences were observed, but no pattern of increase or decrease in growth indices were discernible. The regression was not significant. *N. exaltata* 'Roosevelt' results had a negative quadratic response to increasing levels of FGD gypsum (Fig. 8). Comparison of means varied across treatments, with 19.58 kg • m^{-3} having similar GI as treatments of 6.52, 13.0, and 16.3 kg • m^{-3}. Overall, GI was reduced in response to added FGD gypsum. There were no visual negative effects on the ferns from deficiencies or excesses from increasing rates of FGD gypsum.

With varying responses across the five crops tested in these two studies, there appeared to be no visual symptoms indicating any stress that could be attributed to the lack of or abundance of Ca or S. It is suspected that the Ca contained within the fertilizer used, along with municipal water used, may have contributed to the Ca levels being sufficient for the plants. Analysis of the water used for irrigation was performed after these experiments, and the calcium level was reported to be at 12.38 ppm (Table 4). Tissue analysis was performed for both the geraniums (Table 5) and petunias (Table 6). Petunias showed increasing levels of Ca and S as the rate of gypsum increased while geraniums varied in calcium levels as the rate of gypsum increased. Sulfur levels were all similar with the exception of the DL-only treatment. All levels of Ca and S for each experiment and treatment were within the sufficiency ranges suggested by Mills and Jones (1996). Mean EC levels in both petunia and geranium experiments increased as gypsum increased, and though not statistically significant in the geraniums, there were differences in petunias (Tables 1 and 2). Both experiments indicated an increase EC over the control or for all treatments containing DL.

Growth indices in geraniums did increase slightly, in contrast to a dramatic drop of the mean GI of the petunias. The growth indices for the petunia study were highest at the lowest rate of FGD gypsum applied, decreasing as rates increased, indicating that the low rate of gypsum could be used for increasing the size of the plants, yet the fresh and dry weights did not differ as dramatically in comparison. Growth indices for the ferns varied, though there were not dramatic increases nor decreases in the means.

All three species of plants tested were shown to be tolerant of the higher rates of applied FGD gypsum. Further analysis isolating calcium to being only supplied by the gypsum instead of the fertilizer or water supply used would be merited.

Based on the results of this study, geranium greenhouse production may benefit from incorporating FGD gypsum when using Fafard 3B substrate, as GI increased. In petunia production, it is recommended to use a lower rate of 3.26 kg • m^{-3} FGD gypsum, as GI did increase compared to the control rate of 0 kg/m3. Petunia mean growth index was highest at 3.26 kg • m^{-3} FGD gypsum and decreased by almost half at higher rates. *N. oblierata* and *N. exaltata* 'Bostoniensis' GI increased when compared to the control, and the highest recommended treatment would be 13.0 and 16.3 kg • m^{-3}, respectively. There were no observable detrimental effects to adding additional FGD gypsum, and could provide an alternative source of calcium when pH does not need correcting.

Literature Cited

American Coal Ash Association (ACAA). 2017. 2016 Coal Combustion Product (CCP) Production & Use Survery Report. https://www.acaa-usa.org/Portals/9/Files/PDFs/News-Release-Coal-Ash-Production-and-Use-2016.pdf (Accessed 28 April 2018).

Chen, L., W.A. Dick, and S. Nelson. 2005. Flue gas desulfurization products as sulfur sources for alfalfa and soybean. Agron. J. 97:265-271.

Chen, L. and W.A. Dick. 2011. Gypsum as an agricultural amendment: General use guidelines. Ohio State University Extension.

Chibber, N. 2007. Sulphur deficiency in Madhya Pradesh soil leads to poor harvest. Down to Earth (15 Aug. 2007). http://www.downtoearth.org.in/news/sulphur-deficiency-in-madhya-pradesh-soil-leads-to-poor-harvest-6346 (accessed 16 July 2015).

Crocker, W. 1922. History of the use of gypsum. Gypsum Industries Association, Chicago, IL.

Duke Energy. 2017. Sulfur Dioxide Scrubbers. https://www.duke-energy.com/our-company/environment/air-quality/sulfur-dioxide-scrubbers. Accessed December 2017.

Florida Public Service Commission. 2011. Fact Sheet: Docket No. 110262-EI Petition for approval of new environmental program for cost recovery through the Environmental Cost Recovery Clause. http://www.psc.state.fl.us/Files/PDF/About/Decisions/TECO_Fact_Sheet.pdf (Accessed 13 July, 2016).

Mayfield, J.L., J. Sibley, E. Simonne, and D. Eakes. 2002. Effect of liming materials on media pH and overall growth and nutrition of dwarf Nandina. J. Plant Nutr. 25:1377-1387.

Menge, J.A., H.D. Ohr, E.L.V. Johnson, S. Campbell, F. Guillemet, N. Grech, and E. Pond. 1994. The effect of mulches, gypsum and fungicides on the performance of avocado planted in soil with *Phytophthora cinnamomi* and *P. citricola*. Phytopathology 84:1103.

Mills, H.A. and J.B. Jones. 1996. Plant analysis handbook II: A practical sampling, preparation, analysis, and interpretation guide. Micromacro Publishing, Athens, Georgia, USA, pp. 194, 218.

National Atmospheric Deposition Program. 2015. http://nadp.sws.uiuc.edu/data/animaps.aspx (accessed 15 July 2015).

Nemec, S. and O. Lee. 1995. Management of phythophthora root and crown rot of blight of citrus with soil amendments. Phytopathology 85:1200 (abstr.).

Norton, L.D. 2009. Properties of FGD Gypsum that Provides Value for Agricultural Land Application. Retrieved from: http://www.fgdproducts.org/Presentations_Indy_11.../Tue_1410_Norton.pdf.

Scherer, H. W. (2001). Sulphur in crop production—invited paper. European J. of Agron. 14(2):81-111.

Scott, W.D., B.D. McCraw, J.E. Motes, and M.W. Smith. 1993. Application of calcium to soil and cultivar affect elemental concentration of watermelon leaf and rind tissue. J. Amer. Soc. Hort. Sci. 118:201-206.

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Table 1. Effects of increasing rates of FGD gypsum on *Geranium.*

FGD gypsum (kg/m^3)	GI[zu]	FW[xyu]	DW[xyu]	pH[wu]	EC[wu]
0 (0 lbs/yd^3)	16.60 c	77.48 b	20.66 a	6.55 a	0.52 c
3.26 (5.5 lbs/yd^3)	16.96 bc	86.70 a	21.16 a	6.09 b	1.79 a
6.52 (11 lbs/yd^3)	16.96 bc	81.40 ab	21.56 a	6.12 b	1.69 a
9.78 (16.5 lbs/yd^3)	17.60 ab	82.30 ab	22.96 a	6.14 b	1.85 a
13.0 (22 lbs/yd^3)	17.85 a	79.28 b	22.72 a	6.11 b	2.50 a
3 DL* (5 lbs/yd^3)	17.36 ab	62.40 c	20.68 a	6.55 a	0.72 c
3.26 + 3 DL[v] (5.5 + 5 lbs/yd^3 DL)	17.62 ab	67.66 bc	21.38 a	6.68 a	1.16 b
Significance	L*	Q*	Q*	Q*	Q*

[z] Growth index = $[(\text{height} + \text{width}^1 + \text{width}^2)/3]$.($P \leq 0.05$).

[y] Fresh and dry weights at termination.

[x] Plant fresh and dry weight measured in grams.($P \leq 0.05$).

[w] Mean pH and EC at termination.

[v] DL=dolomitic lime.

[u] Column means within treatment are not significantly different when followed by the same letter.

NS=Not significant; L = linear; or Q = quadratic response at $P \leq 0.05$ based on single degree-of-freedom orthogonal contrasts.

Table 2. Effects of increasing rates of FGD gypsum on *Petunia x hyrbida*.

FGD gypsum (kg/m^3)	GI[z,u]	FW[y,u]	DW[x,u]	pH[w,u]	EC[w,u]
0 (0 lbs/yd^3)	20.81 ab	75.61 a	20.81 ab	6.60 a	0.30 d
3.26 (5.5 lbs/yd^3)	32.1 a	82.06 a	21.11 ab	6.16 a	1.24 c
6.52 (11 lbs/yd^3)	19.4 b	85.29 a	21.61 a	5.94 bc	2.03 b
9.78 (16.5 lbs/yd^3)	10.5 c	83.37 a	21.90 a	6.00 b	2.42 ab
13.0 (22 lbs/yd^3)	7.0 d	82.94 a	21.46 a	5.86 c	2.88 a
3 DL* (5 lbs/yd^3)	7.0 d	80.91 a	20.37 b	6.62 a	0.39 d
3.26 + 3 DL[v] (5.5 + 5 lbs/yd^3 DL)	6.5 d	84.23 a	21.11 ab	6.53 a	1.32 c
Significance*	NS*	NS*	NS*	Q*	L*

[z] Growth index = [(height + width^1 + width^2)/3].($P \leq 0.05$).

[y] Fresh and dry weights at termination.

[x] Plant fresh and dry weight measured in grams ($P \leq 0.05$).

[w] Mean pH and EC at termination.

[v] DL=dolomitic lime .

[u] Column means within treatment are not significantly different when followed by the same letter.

NS=Not significant; L = linear; or Q = quadratic response at $P \leq 0.05$ based on single degree-of-freedom orthogonal contrasts.

Table 3. Effects of increasing rates of FGD gypsum on three cultivars of *Nephrolepis*.

FGD gypsum (kg/m^3)	GI[zyv]	GI[zxv]	GI[zwv]
0 (0 lbs/yd^3)	17.87 ab	14.47 bc	14.38 a
3.26 (5.5 lbs/yd^3)	17.51 b	15.37 abc	13.68 ab
6.52 (11 lbs/yd^3)	17.56 b	14.26 c	12.91 bc
9.78 (16.5 lbs/yd^3)	18.00 ab	15.72 ab	13.65 ab
13.0 (22 lbs/yd^3)	18.96 a	15.30 abc	12.92 bc
16.3 (27.5 lbs/yd^3)	17.10 bc	16.28 a	13.39 bc
19.58 (33 lbs/yd^3)	16.19 c	14.61 bc	12.73 c
Significance[*]	C[*]	NS[*]	Q[*]

[z] Growth index = [(height + width^1 + width^2)/3].($P \leq 0.05$).

[y] *Nephrolepis obliterata* [x] *Nephrolepis exaltata* ‘Bostoniensis’ [w] *Nephrolepis exaltata* ‘Roosevelt’.

[v] Column means within treatment are not significantly different when followed by the same letter.

[*] NS=Not significant; L = linear; or Q = quadratic response; C = cubic at $P \leq 0.05$ based on single degree-of-freedom orthogonal contrasts.

Table 4. Water Analysis for the Paterson Greenhouse Complex*.

pH	Hardness (ppm)	Conductivity (mmhos/cm)	Calcium (ppm)	Potassium (ppm)	Sulfur as SO4 (ppm)	Salt Concentration - TDS (ppm)
7.68	42.29	0.14	12.38	2.26	21.75	88.9

*Paterson Greenhouse Complex, Auburn University, AL.

Table 5. *Geranium* Tissue Analysis*.

FGD gypsum (kg/m^3)	Ca (%)	K (%)	Mg (%)	P (%)	Al (ppm)	B (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Na (ppm)	Zn (ppm)	N (%)	S (%)
0 (0 lbs/yd^3)	0.84	1.67	0.98	0.19	48	26	27	71	37	1295	39	2.24	0.35
3.26 (5.5 lbs/yd^3)	1.13	1.61	0.7	0.23	35	28	15	77	41	1033	55	2.78	0.35
6.52 (11 lbs/yd^3)	1.15	1.75	0.81	0.19	54	30	16	88	41	1309	62	2.79	0.40
9.78 (16.5 lbs/yd^3)	1.05	1.36	0.56	0.17	64	23	18	52	36	589	25	2.38	0.35
13.0 (22 lbs/yd^3)	0.74	1.42	0.48	0.19	61	20	13	55	24	652	33	2.26	0.31
3 DL* (5 lbs/yd^3)	0.9	1.23	0.6	0.14	58	16	25	37	14	555	7	1.75	0.19
3.26 + 3 DL[v] (5.5 + 5 lbs/yd^3 DL)	1.04	1.47	0.56	0.14	71	33	18	49	28	607	32	1.86	0.35

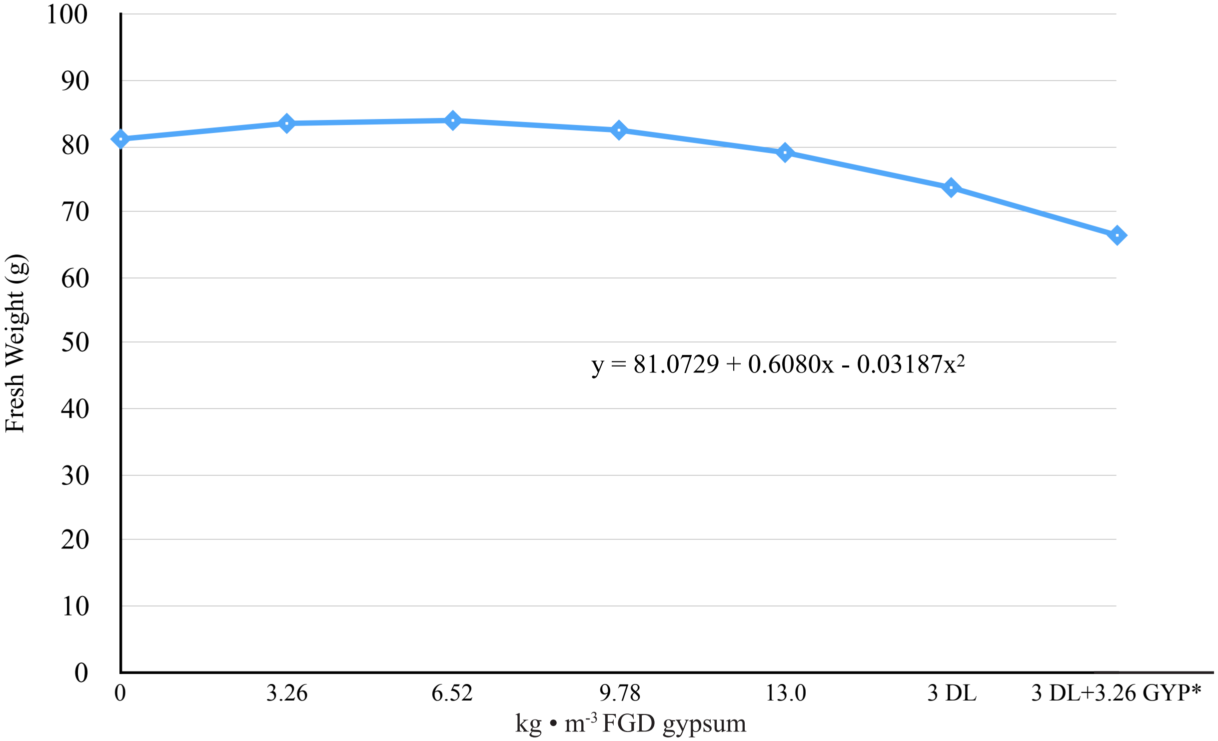
*Analysis performed by Auburn University Soil Testing Laboratory.

Table 6. *Petunia* Tissue Analysis*.

FGD gypsum (kg/m^3)	Ca (%)	K (%)	Mg (%)	P (%)	Al (ppm)	B (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Na (ppm)	Zn (ppm)	N (%)	S (%)
0 (0 lbs/yd^3)	0.91	2.76	1.27	0.29	174	33	40	113	39	2950	44	2.99	0.85
3.26 (5.5 lbs/yd^3)	1.68	2.69	1.05	0.30	197	31	38	147	24	2206	53	3.10	1.13
6.52 (11 lbs/yd^3)	1.78	2.44	1.00	0.29	305	28	36	198	29	2014	54	2.73	1.62
9.78 (16.5 lbs/yd^3)	2.23	2.64	0.90	0.26	101	28	43	106	30	1596	65	3.11	1.99
13.0 (22 lbs/yd^3)	2.11	2.49	0.98	0.20	194	29	57	154	28	1622	82	3.08	2.03
3 DL* (5 lbs/yd^3)	1.12	2.17	0.87	0.28	418	20	29	156	24	2020	56	3.67	0.81
3.26 + 3 DL^v (5.5 + 5 lbs/yd^3 DL)	2.27	2.66	1.03	0.34	300	24	34	213	22	2222	65	2.97	1.25

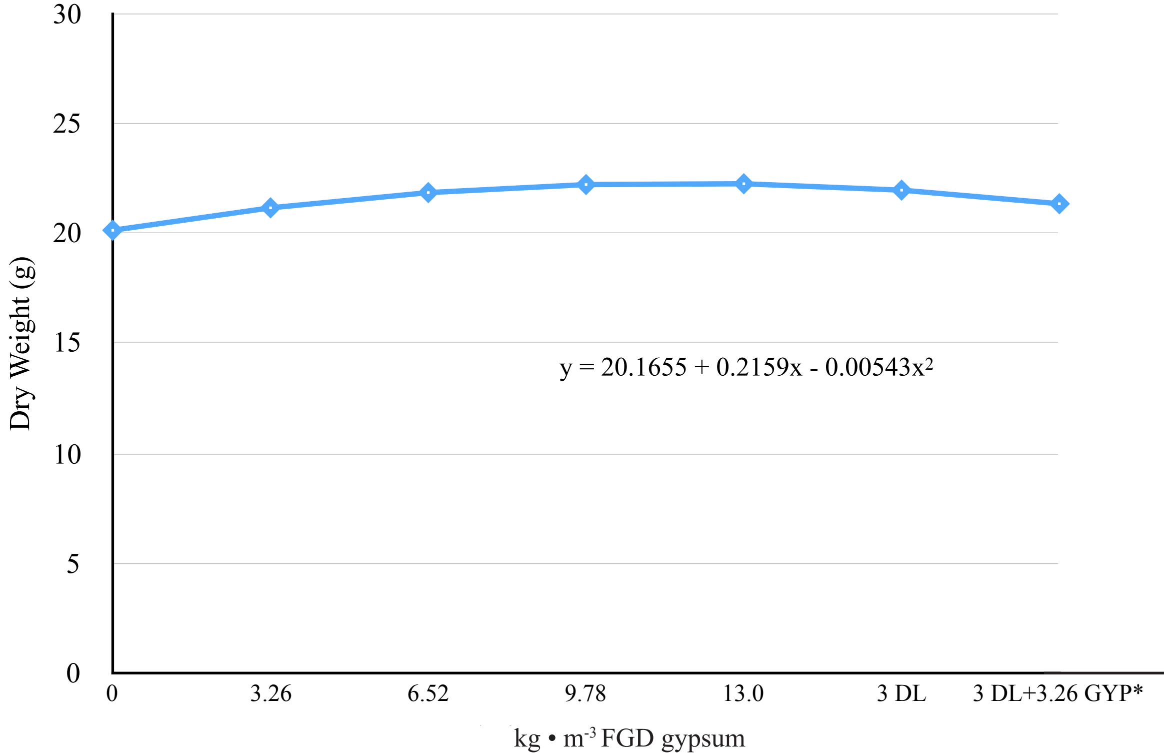
*Analysis performed by Auburn University Soil Testing Laboratory.

Fig. 1. Effects of the incorporation of FGD gypsum into the substrate of geranium on fresh weights.



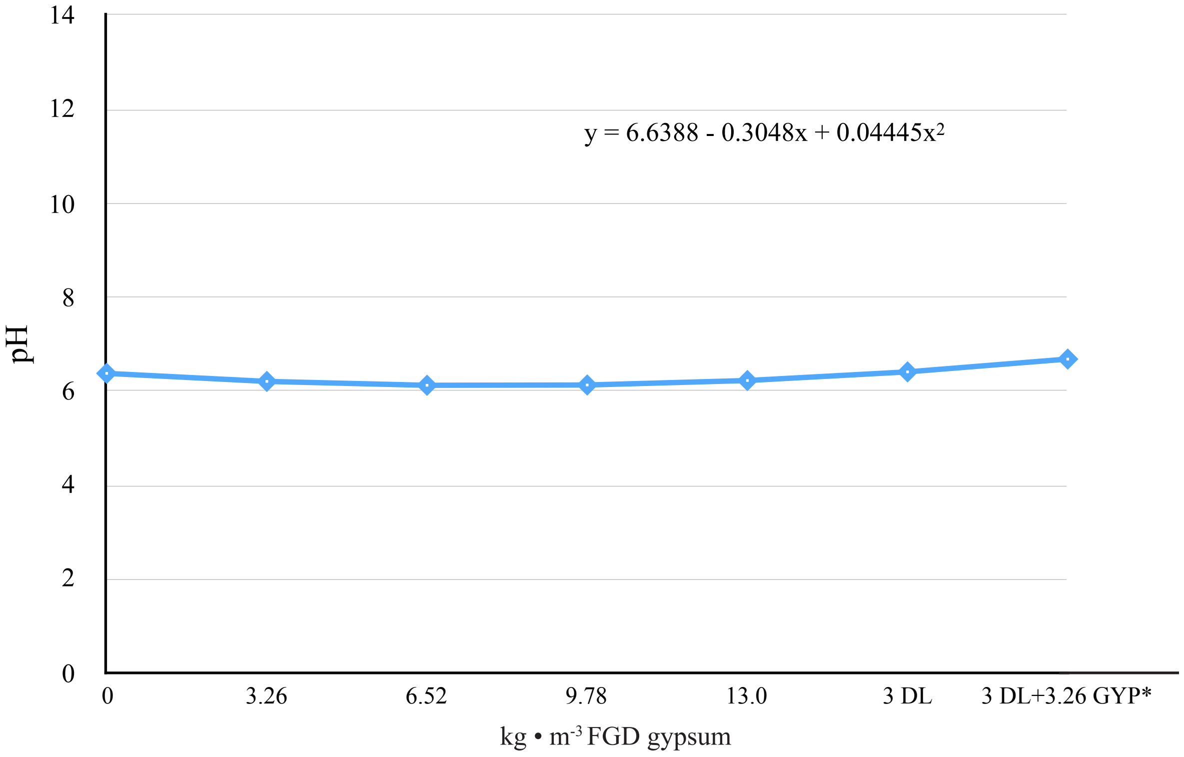
*DL = Dolomitic lime, GYP = FGD gypsum

Fig. 2. Effects of the incorporation of FGD gypsum into the substrate of geranium on dry weights.



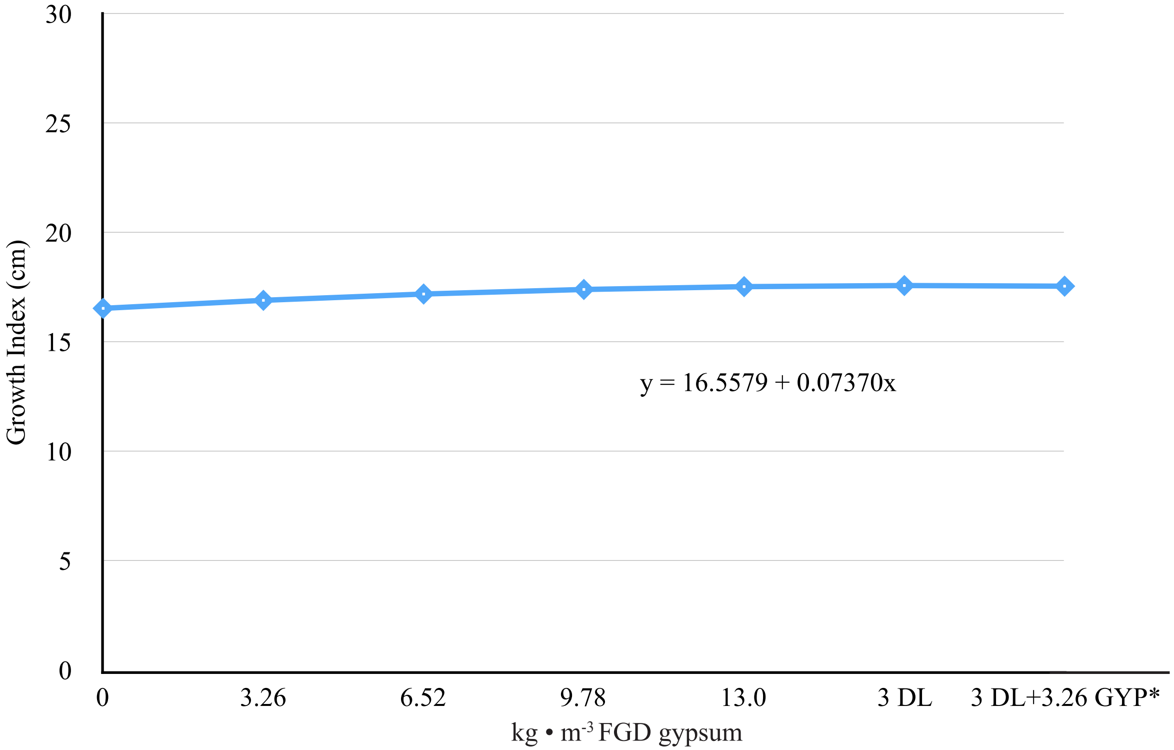
*DL = Dolomitic lime, GYP = FGD gypsum

Fig. 3. pH response of added FGD gypsum incorporated into the substrate of geraniums.



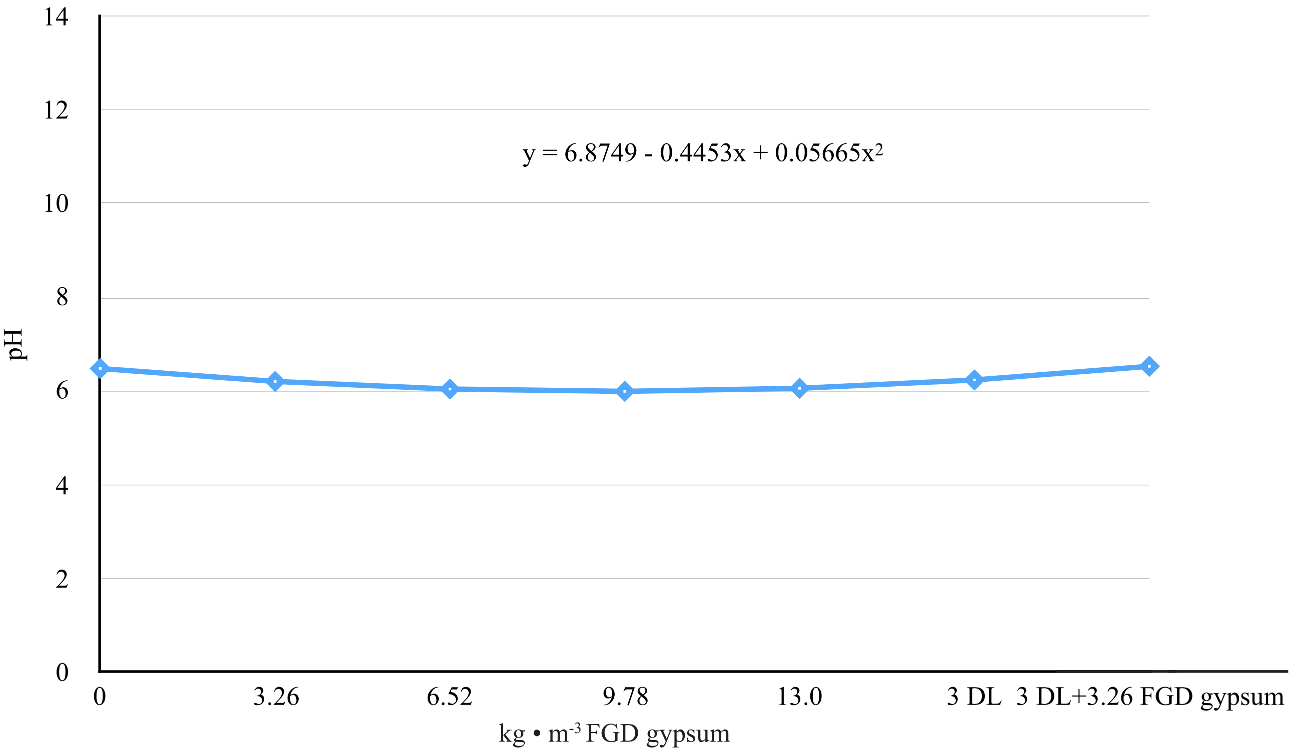
*DL = Dolomitic lime, GYP = FGD gypsum

Fig. 4. Effects of the incorporation of FGD gypsum into the substrate of geranium on growth index.



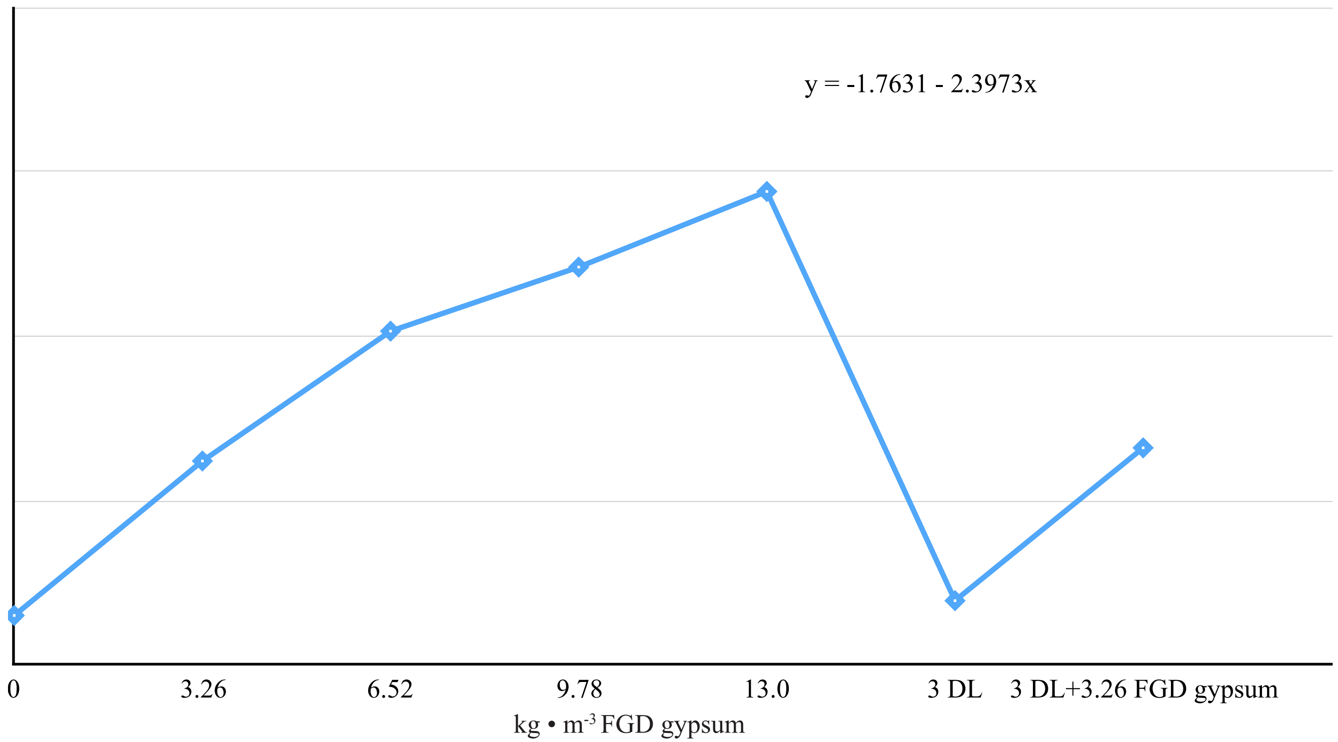
*DL = Dolomitic lime, GYP = FGD gypsum

Fig. 5. pH response of added FGD gypsum incorporated into the substrate of petunias.



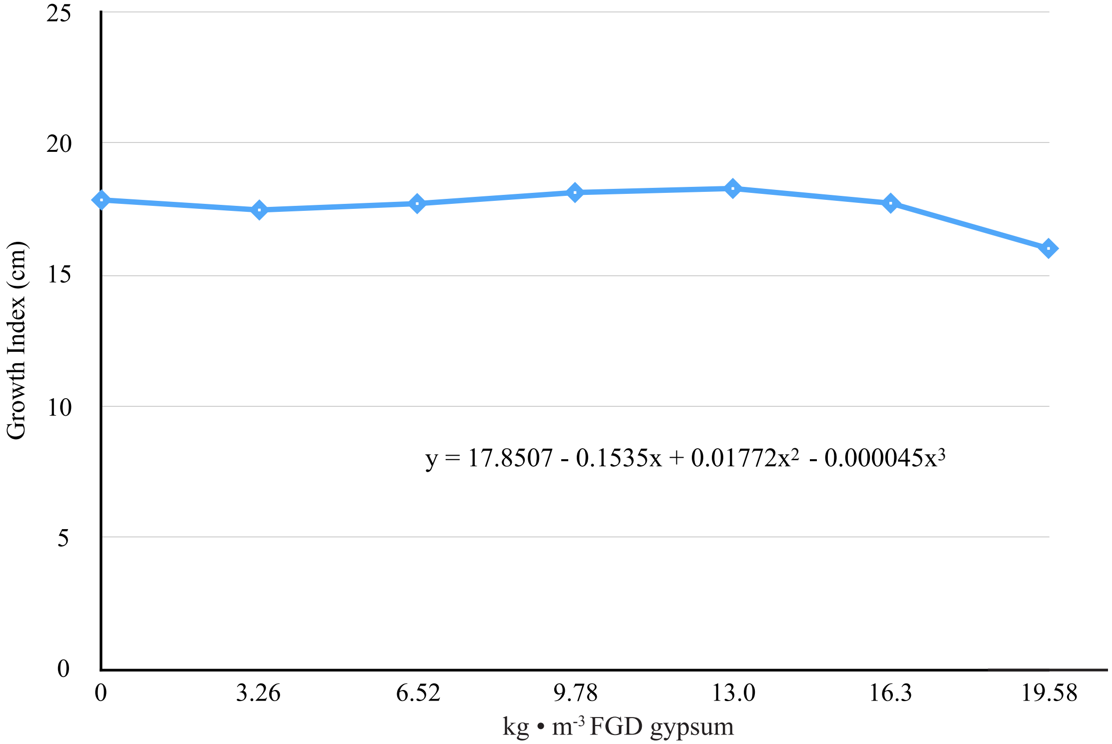
*DL = Dolomitic lime, GYP = FGD gypsum

Fig. 6. Effects of the incorporation of FGD gypsum into the substrate of geranium on electrical conductivity.



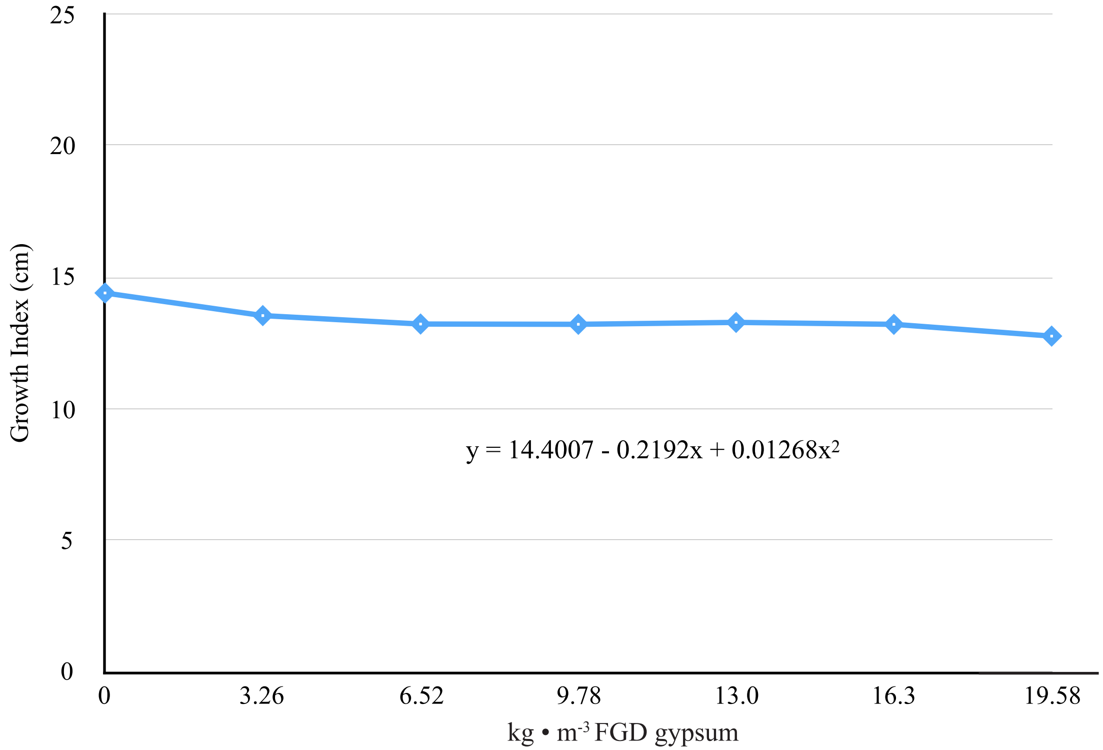
*DL = Dolomitic lime, GYP = FGD gypsum

Fig. 7. Effects of the incorporation of FGD gypsum into the substrate of *N. obliterata*, Australian fern, on growth index.



*DL = Dolomitic lime, GYP = FGD gypsum

Fig. 8. Effects of the incorporation of FGD gypsum into the substrate of *N. exaltata* ‘Roosevelt’ on growth index.



*DL = Dolomitic lime, GYP = FGD gypsum

CHAPTER IV

Influence of FGD Gypsum on Stem Strength of Poinsettia

Abstract. Flue gas desulfurization (FGD) gypsum is a byproduct from coal-fired electricity production facilities that can be used as a source of calcium for plants to provide cell wall stability and stem strength, a major problem in poinsettia production. The objective of this study was to determine if increasing rates of FGD gypsum to provide additional calcium would reduce the occurrence of stem breakage of 'Freedom Red' poinsettias (*Euphorbia pulcherrima* Willd. ex Klotzsch). A Fafard 3B substrate was used for a study using FGD gypsum rates of 0, 3.26, 6.52, 9.78, 13.0, 16.3, and 19.5 kg • m^{-3} (0, 5.5, 11, 16.5, 22, 27.5, and 33 lbs • yd^{-3}) as well as an additional treatment of 3 kg/m3 dolomitic lime incorporated preplant. A second study used significantly higher rates of 0, 9.78, 19.58, 29.37, 39.16, 48.95, and 58.74 kg • m^{-3} (0, 16.5, 33, 49.5, 66, 82.5, and 99 lbs • yd^{-3}) of FGD gypsum. Stem strength was measured using a digital force gauge clamped to similarly sized lower branches 10 cm from the main branch to record the maximum force at breakage when pulling perpendicular away from the main stem. Results from the first experiment indicated stem strength was highest in the control, and was similar to all treatments except for the treatment of 3.26 kg • m^{-3} FGD gypsum, which had the lowest stem strength. The second experiment indicated a slight increase in stem strength at FGD gypsum rate of 19.58 kg • m^{-3}. Stem strength for higher rates

of FGD gypsum were different than the control and 9.78 kg • m^{-3}, however still may not be enough stem strength to overcome breakage when moving plants or shipping to consumers.

Introduction

Poinsettias (*Euphorbia pulcherrima* Willd. ex Klotzsch) is the most important indoor flowering potted plants in the United States, representing almost 20% of the potted flowering plant market (USDA, 2016). One of the major problems that plague growers with the production and transportation of poinsettias is poor lateral stem strength, which often results in breakage of the branches, rendering them unattractive and unmarketable. Several studies have explored the causation of weak stem strength including: spacing of the plants (Faust et al., 1997; Nell et al., 1996), nitrogen fertilizer rates (Rose and White, 1994), lack of calcium uptake and distribution in the plant (Lawton et al., 1989), stem diameter (Faust et al., 1997; Nell and Leonard, 1996), and plant growth regulators (PGRs) (Kuehny and Branch, 2000; McDaniel et al., 1990). In one study, the stem strength of 'Freedom Red' poinsettias was shown to be greater when fertilizing with high nitrate nitrogen with added calcium (Kuehny and Branch, 2000). The study suggested that the greater stem strength would be attributed to increased calcium uptake, leading to stronger cell walls (Marschner, 1986).

In the container-grown nursery industry, studies have investigated the effects of incorporation of Ca-containing materials such as limestone (Mayfield, 2002; Wright, 1999) and have shown that container-grown plants grow well in organic substrates at a pH range of 5 to 5.5 (Bunt, 1998; Lucas and Davis, 1961). Mineral soils exhibit different soil chemistries from soilless substrates, and the need for pH correction using lime has been questioned (Mayfield, 2002), though Ca may still be insufficient for some crops for normal physiological function and plant growth. Agricutural gypsum resulted in greater growth and increased foliar nutrient levels compared to agricultural limestone for plants grown in organic substrate (Mayfield, 2002).

One possible way of availing calcium to container-grown plants is through the addition of gypsum to the substrate. Gypsum (calcium sulfate dihydrate ($CaSO_4 \cdot 2 H_2O$) is a naturally occurring colorless and odorless very fine textured solid mineral, with a particle size typically finer than 50 µm (Norton, 2009). Gypsum is usually mined from natural deposits in the earth, but can also be produced synthetically as a byproduct from burning of high sulfur-containing coal, typically from electricity generating power plants. These coal-burning power plants contain what is generally referred to as a scrubber system. A scrubber system is the informal name for flue gas desulfurization (FGD) technology, which removes SO_2 emissions from the exhaust of coal-fired power plants. A scrubber works by spraying a wet slurry of limestone into a large chamber where the calcium in the limestone reacts with the SO_2 in the flue gas. The SO_2 exhaust gas passes through the scrubber where a spray mixture of limestone (or other chemical reagent) and water reacts with the SO_2. The reaction traps the SO_2 before it is released into the atmosphere. When SO_2 combines with the limestone spray mixture, the primary byproduct produced is known as flue gas desulfurization gypsum (FGD) gypsum, suitable for beneficial uses in the same way as mined gypsum (Duke Energy, 2017). FGD gypsum is chemically comparable to mined gypsum, although each may contain different impurities at trace levels. Recent estimations indicate that mined gypsum accounts for an estimated 11.5 million tons, while synthetic forms account for an estimated 11.5 million tons in the United States (USGS, 2016). Of the total gypsum produced in the U.S., either mined, or synthetically from coal-fired power plants, an overwhelming majority is used in the wallboard industry. Because FGD gypsum is comparable to mined gypsum there is a significant potential for greater FGD gypsum application and use in horticulture. The objective of this study was to determine if additional calcium from increasing rates of FGD gypsum incorporated in the substrate could reduce the occurrence of stem breakage of ‘Freedom Red’ poinsettias.

Materials and Methods

Two experiments were conducted in greenhouses located at the Paterson Greenhouse Complex, Auburn University, AL (32.596965, -85.488019) in August 2013 and repeated in 2013 at the Ornamental Horticulture Research Center greenhouses in Mobile, Alabama (30.702305, -88.145643) beginning in August 2014. Both experiments were conducted using ‘Freedom Red’ poinsettias (*Euphorbia pulcherrima* ‘Freedom Red’) grown from rooted cuttings transplanted into 6” pots. A Fafard 3B (Sun Gro Horticulture, Agawam, MA) substrate was prepared by preplant incorporating FGD gypsum rates of 0, 3.26, 6.52, 9.78, 13.0, 16.3, and 19.5 kg • m^{-3} (0, 5.5, 11, 16.5, 22, 27.5, and 33 lbs • yd^{-3}) as well as an additional treatment of 3 kg • m^{-3} dolomitic lime. The experiment was arranged in a randomized complete block design with 13 repetitions. There were no micronutrients or other amendments added preplant to the substrate. Plants were fertilized throughout the growing period using 15-5-25 Poinsettia Peat Lite Special (JR Peters, Inc.) fertilizer that contained no calcium and greater than 70% nitrate nitrogen with a micronutrient package adjusted for poinsettias (lower boron and increased magnesium, zinc, and molybdenum) in order to isolate the calcium source from the incorporation of FGD gypsum treatments. The plants were pinched to induce branching in September 2013. Plants were grown to a marketable size (approximately 30 to 45 cm) with data collected on each treatment including: dry weights, stem strength, growth index, and plant tissue analysis. Stem strength was measured using a digital force gauge (Chatillon model E-DFE-025, AMETEK, Inc.) clamped to similarly sized lower branches 10 cm from the main branch to record the maximum force at breakage when pulling perpendicular away from the main stem. A constant force was applied to the branch at a perpendicular angle of the main stem until the branch broke and maximum force (N) recorded.

The second experiment was a repeat of the first (completed in 2013) at the Ornamental Horticulture Research Center greenhouses in Mobile, Alabama (30.702305, -88.145643) the following year in 2014 under the same parameters as the first experiment, with the exception of drastically increased rates of incorporated FGD gypsum. Based on the results of the first experiment, extremely high rates of FGD gypsum were used to investigate if these higher rates would the affect stem strength of poinsettia. The rated of FGD gypsum used were 0, 9.78, 19.58, 29.37, 39.16, 48.95, and 58.74 kg • m^{-3} (0, 16.5, 33, 49.5, 66, 82.5, and 99 lbs • yd^{-3}), arranged in a randomized complete block design with thirteen replications per treatment. The data collected were dry weights and stem strength and tissue analysis was performed.

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). Where residual plots and a significant

COVTEST statement using the HOMOGENEITY option indicated heterogeneous variance, a RANDOM statement with the GROUP option was used to correct heterogeneity. All reported means are least squares means. All significances were at $\alpha=0.05$. All plants were grown to a uniform marketable size of 25 cm height and 35 cm x 35 cm width.

Results and Discussion

In the first experiment, the highest stem strength was observed with the control, with similar stem strengths for all other treatments at 6.52 kg • m^{-3} and above (Table 1). Stem strength was lowest for FGD gypsum treatment of 3.26 kg • m^{-3}. Regression analysis was not significant for stem strength. Dry weights for all treatments showed no mean differences, although there was a negative quadratic response (Fig. 1). The maximum dry weight was at the 6.52 kg • m^{-3} rate, decreasing as rates of FGD gypsum increased (Table 1). Means of growth indices varied across all treatments, and means were similar for the control, the treatment of dolomitic lime, 9.78, 13.0, and 16.3 kg • m^{-3}, with the highest GI being at the 6.52 kg • m^{-3} rate. Regression for growth indices was not significant.

Tissue analysis (Table 3) indicated Ca percentage levels increased with higher rates of FGD gypsum, though the Ca percentage was similar in treatments above 13.0 kg • m^{-3}, including the treatment of DL. The S percentage levels indicated a similar pattern as Ca in that FGD gypsum rates increased the S percentage up to 13.0 kg • m^{-3}, then leveled to a similar percentage for the higher two FGD gypsum treatment rates, with the DL treatment similar. N percentage was consistent across all FGD gypsum treatments, as well as the DL treatment.

The second experiment with the higher rates of FGD gypsum did show increasing stem strength with increasing rates of FGD gypsum (Table 2). The control of 0 kg • m^{-3} FGD gypsum had the lowest stem strength and the 9.78 kg • m^{-3} gypsum rate was similar to the control treatment. The regression was not significant for stem strength. Dry weight means varied across treatments with the maximum observed dry weight at the FGD gypsum rate of 48.95 kg • m^{-3}. Regression was not significant for dry weights in this experiment.

Tissue anaylsis (Table 4) for the second experiment indicated that Ca percentage levels were similar for all treatments, as well as S percentage levels were consistent across all treatments of FGD gypsum.

During both experiments, no observable bract necrosis or bract edge burn on any treatment, which can occur in poinsettias when there is a lack of Ca, and sufficiency levels were within the recommended range (Jones, et al., 1991). The Ca contained within FGD gypsum could be used as a preventative measure to control bract edge burn, as shown by Barrett et. al. (Barrett, et al., 1995). Tissue analysis did not reveal differences within treatments in the second experiment. It is suspected that the Ca concentration in the irrigation water could have factored into the analysis, as the second experiment was performed at the Ornamental Research Station greenhouses in Mobile, AL.

Stem strength in the second experiment increased with increasing rates of FGD gypsum, however, the total strength may not be enough to overcome the problem of stem breakage when moving plants to be shipped to the consumers. The means of stem strengths from the first experiment were comparable to the stem strength of the second experiment, though the higher rates of FGD gypsum in the second experiment indicated higher stem strength. In a study on stem strength of poinsettias, the greatest stem strength was attributed to a high nitrate nitrogen fertilizer and added calcium (Kuehny et al., 2000). Fertilizers high in NH_4NO_3 have been associated with reduced Ca concentrations in some plants, whereas nitrate nitrogen stimulated cation uptake (Kuehny, et al., 2000; Quebedeaux and Osbun, 1973; Marti and Mills, 1991; Heuer, 1991). The results of this study suggest that additional calcium contained within FGD gypsum may not contribute to an increased stem strength but the high nitrate nitrogen contained in the fertilizer (70%) applied across all treatments increased calcium uptake. FGD gypsum could therefore be used as a Ca supplement to a nitrate nitrogen fertilizer to help prevent low Ca levels causing detrimental effects such as bract edge when growing poinsettias.

Literature Cited

Barrett, J.E., T.A. Nell, T.J. Blom, and P.A. Hammer. 1995. Poinsettia bract edge burn: potential causes and role of calcium sprays and botrytis. HortScience 30:771. (abstr.).

Bunt, A.C.1988. Media Mixes for Container-Grown Plants, 2nd ed. Unwin Hyman Ltd., London, England.

Duke Energy. 2017. Sulfur Dioxide Scrubbers. https://www.duke-energy.com/our-company/environment/air-quality/sulfur-dioxide-scrubbers. Accessed December 2017.

Faust, J.E., E. Will, X. Duan, and E.T. Graham. 1997. Whole plant and histological analysis of poinsettia stem breakage. HortScience 32:509. (abstr.).

Heuer, B. 1991. Growth, photosynthesis and protein content in cucumber plants as affected by supplied nitrogen form. J. Plant Nutr. 14: 363-373.

Jones, J.B. Jr., B. Wolf, and H.A. Mills. 1991. Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide. Micro-Macro Publishing, Athens, GA.

Kuehny, J.S., P.C. Branch, and P.W. Adams. 2000. Stem strength of poinsettia. Acta Hortic. 515:257-264.

Lawton, K.A., G.L. McDaniel, E.T. Graham. 1989. Nitrogen source and calcium supplement affect stem strength of poinsettia. HortScience 24:463-465.

Lucas, R.E., and J.K. Davis. 1961. Relationships between pH values of organic soils and availabilites of 12 plant nutrients. Soil Sci. 92:177-182.

Mayfield, J.L., J. Sibley, E. Simonne, and D. Eakes. 2002. Effect of liming materials on media pH and overall growth and nutrition of dwarf Nandina. J. Plant Nutr. 25:1377-1387.

Marschner, H. 1986. Marschner's Mineral Nutrition of Higher Plants. Academic Press.

Marti, H.R. and H.A. Mills. 1991. Calcium uptake and concentration in bell pepper plants as influenced by nitrogen form and stages of development. J. Plant Nutr. 14:1177-1185.

McDaniel, G.L., T.G. Effin, K.R. Maleug. 1990. Alteration of poinsettia stem anatomy by growth-retarding chemicals. HortScience 25:433-435.

National Agricultural Statistics Service, United States Department of Agriculture. 2016. Floriculture Crops 2015 Summary. http://usda.mannlib.cornell.edu/usda/current/FlorCrop/FlorCrop-04-26-2016.pdf. (accessed April 2018).

Nell, T.A. and R.T. Leonard. 1996. Protecting Poinsettias from Postproduction Losses. GrowerTalks July, pp. 98-104.

Norton, L.D. 2009. Properties of FGD Gypsum that Provides Value for Agricultural Land Application. Retrieved from: http://www.fgdproducts.org/Presentations_Indy_11.../Tue_1410_Norton.pdf. (accessed July 2013).

Quebedeaux, B. Jr. and J.L. Osbun. 1973. Effect of ammonium nutrition on water stress, water uptake and root pressure in *Lycopersicon esculentum* Mill. Plant Physiology 52:677-679.

Rose, M.A. and J.W. White. 1994. Nitrogen rate and timing of nitrogen application in poinsettia (*Euphorbia pulcherrima* Willd. Ex Koltz.). HortScience 29:1309-1313.

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United States Geological Survey (USGS). 2016. Mineral Commodity Summaries.http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/mcs-2016-gypsu.pdf (accessed 6 July 2016).

Wright, A.N., A.X. Niemiera, J.R. Harris, and R.D. Wright. 1999. Micronutrient fertilization of woody seedlings essential regardless of pine bark pH. J. Environ. Hort. 17:69-72.

Table 1. Effects of increasing rates of FGD gypsum on dry weights, growth index, and stem strength of poinsettia.

FGD gypsum	DW^{zx}	GI^{yx}	Stem Strength (N)^{x}
0 kg/m^3	51.66 a	478.67 bc	3.51 a
3.26 kg/m^3	47.16 a	466.43 c	2.53 b
6.25 kg/m^3	54.20 a	508.33 a	2.59 ab
9.78 kg/m^3	50.70 a	490.71 ab	2.96 ab
13.0 kg/m^3	47.57 a	493.33 ab	3.18 ab
16.3kg/m^3	46.29 a	470.71 bc	2.89 ab
19.5 kg/m^3	50.35 a	507.38 a	3.44 ab
3 kg/m^3 dolomitic lime (DL)	51.25 a	477.86 bc	2.85 ab
Significance	Q*	NS*	NS*

[z] Shoot dry weight measured in grams. ($P \leq 0.05$).

[y] Growth index = [(height + width^1 + width^2)/3].($P \leq 0.05$).

[x] Column means within treatment are not significantly different when followed by the same letter.

*[NS] Nonsignificant; L = linear; or Q = quadratic response at $P \leq 0.05$ based on single degree-of-freedom orthogonal contrasts.

Table 2. Effects of increasing rates of FGD gypsum on dry weights and stem strength of poinsettia.

FGD gypsum	DW[zy]	Stem Strength (N)[y]
0 kg/m^3	28.49 bc	3.07 b
9.78 kg/m^3	26.68 c	3.13 b
19.58 kg/m^3	34.18 ab	4.04 ab
29.37 kg/m^3	28.55 bc	5.48 a
39.16 kg/m^3	28.50 bc	4.26 a
48.95 kg/m^3	39.17 a	5.58 a
58.74 kg/m^3	29.26 bc	5.46 a
Significance	NS*	NS*

[z] Shoot dry weight measured in grams. ($P \leq 0.05$).

[y] Column means within treatment are not significantly different when followed by the same letter.

*[NS] Nonsignificant; L = linear; or Q = quadratic response at $P \leq 0.05$ based on single degree-of-freedom orthogonal contrasts.

Table 3. Poinsettia tissue analysis (2013)*.

FGD gypsum (kg • m^{-3})	Ca (%)	K (%)	Mg (%)	P (%)	Al (ppm)	B (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)	N (%)	S (%)
0	0.35	3.06	0.48	0.54	10.60	62.50	4.90	166.67	149.33	29.43	3.77	0.33
3.26	0.46	3.30	0.46	0.51	10.50	53.57	3.67	365.33	163.33	29.17	3.72	0.36
6.52	0.63	3.05	0.40	0.54	11.13	50.13	5.27	308.00	130.00	28.43	3.85	0.38
9.78	0.83	3.28	0.38	0.56	11.47	57.77	5.77	175.33	132.33	34.00	3.97	0.50
13.0	0.91	3.16	0.40	0.55	12.03	58.03	5.40	158.00	159.67	31.90	3.72	0.59
16.3	0.89	3.22	0.38	0.56	10.80	49.90	4.93	177.33	149.67	32.60	3.36	0.59
19.5	0.91	3.14	0.37	0.60	11.73	52.23	5.47	188.33	144.67	33.77	3.61	0.54
3 DL^{z}	0.93	3.02	0.36	0.53	10.23	53.17	5.43	308.00	145.33	31.90	3.31	0.54

*Analysis performed by Brookside Laboratories, Inc., New Bremen, OH.

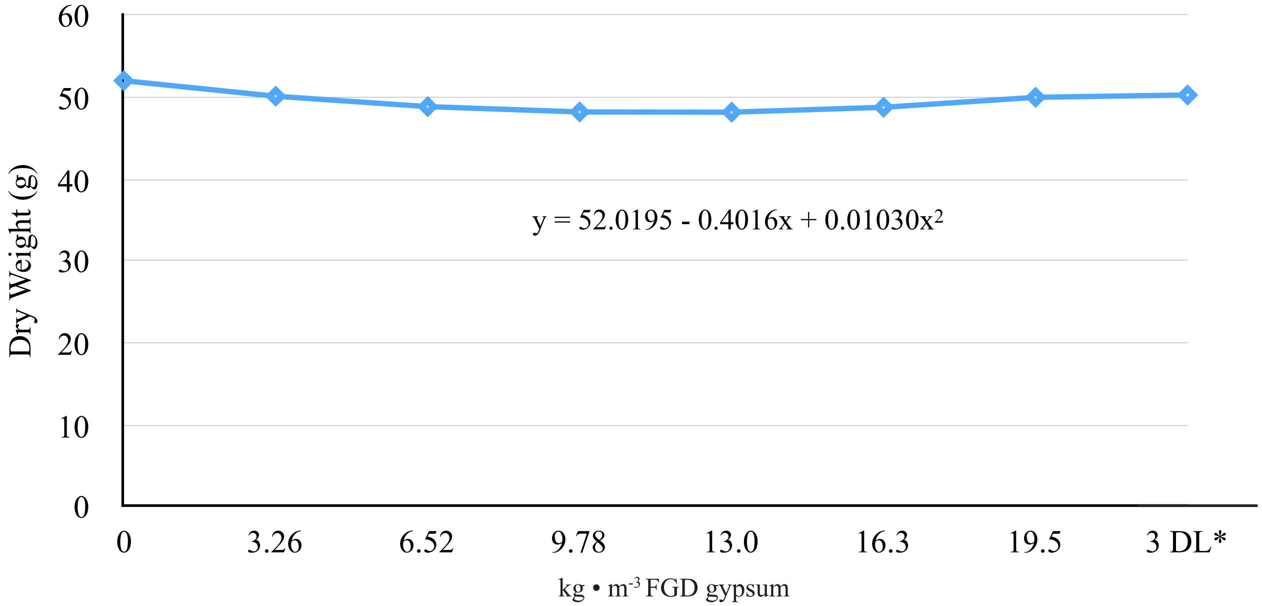
^{z}Dolomitic lime.

Table 4. Poinsettia tissue analysis (2014)*.

FGD gypsum (kg • m^{-3})	Ca (%)	K (%)	Mg (%)	P (%)	Al (ppm)	B (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)	N (%)	S (%)
0	5.31	1.67	0.98	0.88	29	81	2	161	105	33	5.31	0.46
3.26	5.05	1.61	0.78	1.01	23	72	3	198	155	36	5.05	0.52
6.52	4.71	1.75	0.61	0.81	17	70	2	137	133	33	4.71	0.48
9.78	5.45	1.36	0.76	0.92	15	80	3	156	248	34	5.45	0.54
13.0	5.53	1.42	0.70	0.94	14	74	2	159	163	36	5.53	0.54
16.3	5.33	1.23	0.70	0.78	13	68	2	116	153	36	5.33	0.52
19.5	5.58	1.47	0.63	1.00	11	73	2	131	134	35	5.58	0.51

*Analysis performed by Brookside Laboratories, Inc., New Bremen, OH.

Fig. 1. Effect of increasing rates of FGD gypsum on the dry weights of poinsettia.



*Dolomitic lime.

CHAPTER V

Evaluation of FGD Gypsum Stability in Soilless Substrates Under Typical Greenhouse Irrigation Practices

Abstract. Gypsum has been used as an amendment to soilless substrates in many studies for additional calcium made available for plant growth and development. This study evaluated the stability of supplemental FGD gypsum in two soilless substrate blends commonly used in greenhouse crop production: a pinebark and sand mixture and Fafard 3B. Treatments of FGD gypsum at 3.26, 6.52, 9.78, 13.0 kg • m^{-3}, and a treatment of 3.0 kg • m^{-3} dolomitic lime as well as a control of 0.0 kg • m^{-3} were incorporated into the two soilless substrates and put into clear PVC substrate columns. Then the columns were filled with tap water to container capacity and leachate was collected for each treatment. Calcium levels were determined from leachates from each treatment using a LAQUAtwin Ca^{2+} handheld calcium meter. Leachate samples were gathered for a period of sixteen days. Results show that FGD gypsum is rapidly leached from the substrate column. Therefore, FGD gypsum does not appear to be to be suitable for long-term supply of calcium and sulfur, and is not likely to provide reduction of phosphorus or other nutrients in leachates from soilless substrates. Specifically, our data shows that FGD gypsum incorporated into a soilless substrate washes out of the container in very few irrigation events when a standard irrigation regimen target of 10% leaching fraction is used.

Introduction

Gypsum (calcium sulfate dihydrate ($CaSO_4 \cdot 2\ H_2O$) is a naturally occurring colorless and odorless very fine textured solid mineral, with a particle size typically finer than 50 µm (Norton, 2009). Gypsum was one of the earliest forms of nutrient sources for plants and soil conditioners dating back to the late 18th century (Crocker, 1922). Gypsum is usually mined from natural deposits in the earth, but can also be produced synthetically as a byproduct from burning high sulfur-containing coal, typically from electricity generating power plants. These coal-burning power plants contain what is generally referred to as a scrubber system. A scrubber system is the informal name for flue gas desulfurization (FGD) technology, which removes SO_2 emissions from the exhaust of coal-fired power plants. A scrubber works by spraying a wet slurry of limestone into a large chamber where the calcium in the limestone reacts with the SO_2 in the flue gas. Once sulfur is burned and produces SO_2, the exhaust gas passes through the scrubber where a spray mixture of limestone (or other chemical reagent) and water reacts with the SO_2 removed before it is released into the atmosphere. When SO_2 combines with the limestone spray mixture, primary byproduct produced from this process is known as flue gas desulfurization (FGD) gypsum which is then suitable for beneficial uses in the same way as mined gypsum (Duke Energy, 2017). Although many other industries utilize the majority of FGD gypsum produced, agriculture represents the smallest percentage of current usage, but offers one of the greatest potentials for increased use of FGD gypsum. Currently, approximately 500,000 tons of FGD gypsum is used in agriculture (USGS, 2013), represents about 4% of all the FGD gypsum produced in the United States (ACAA, 2014).

Gypsum has been shown to improve overall plant growth, improve soil physical and chemical properties, aid in sodic soil reclamation, and supply the essential plant nutrients Ca and S. The Ca and S contained within FGD gypsum are readily utilized as nutrients in plants due to the solubility of gypsum ($2.5\ g \cdot L^{-1}$ at $20^{\circ}C$) and small and uniform particle size (<150 microns) (Chen and Dick, 2011). Using gypsum as a source for Ca for plant nutrition (Chen et al., 2005) is common throughout the southern United

States as a source of Ca for high Ca-requiring crops, such as peanuts. Gypsum has been shown to significantly increase plant growth, yield, and root growth, as well as reducing *Phythophthora citricola* incidence (Menge, et al., 1994). Sulfur supplied by gypsum was shown to be useful where S was depleted due to factors such as use of fertilizers with little or no S content (Scherer, 2001), and less S deposition from the atmosphere (National Atmospheric Deposition Program, 2015). With deficiencies of S increasing worldwide (Chibber, 2007), gypsum could also provide the needed S on deficient soils (Chen et al., 2005).

Ground dolomitic limestone ($CaCO_3/MgCO_3$) is typically used throughout the southeastern United States as a fertilizer amendment to soilless media. One study observed that plants amended with CaO, agricultural gypsum ($CaSO_4 \cdot 2\ H_2O$), or pelletized dolomitic limestone, were of similar or better quality than plants amended with ground dolomitic limestone (Mayfield, et al., 2002). The study concluded that CaO, CaO/MgO/ $CaCO_3$ blends, $CaSO_4 \cdot 2\ H_2O$, or pelletized limestone may serve as suitable alternatives to ground dolomitic limestone for use in soilless media (Mayfield, et al., 2002).

Preplant incorporation of ground limestone is an accepted practice at nurseries all across the United States, and lime is also the main source of fertilizer Ca and Mg for nursery stock (Mayfield, et al., 2002). However, soilless media chemistry is different from that of mineral soil, and in recent years, research has questioned the need for limestone in soilless substrates, stating the ability of container-grown plants to grow at a pH range of 5.0 to 5.5 in organic media (Bunt, 1988; Lucas and Davis, 1961), which is lower compared to pH ranges required for plants growing in mineral soils (pH 5.8-6.8) (Mayfield, et al., 2002).

There are many studies that have included gypsum as a preplant amendment, but very little research has focused solely on the effect of gypsum on nursery and greenhouse-grown crops. However, due to the high solubility of gypsum and small sparticle size, it is suspected that gypsum incorporated into a commonly used substrates such as pinebark:sand mixtures, or commerically available soilless growing mixes will leach from the container. The objective of this study was to evaluate the stability of supplemental FGD gypsum in two soilless substrate blends commonly used in greenhouse crop production.

Materials and Methods

This study was conducted at the Paterson Greenhouse Complex greenhouses at Auburn University. Substrate columns were built using clear PVC pipes. The columns were 10 cm in diameter and 25 cm long and were mounted on a flat acrylic base using epoxy (Figure 1) with joined pieces sealed using silicone sealant. A hole was drilled into the bottom of the acrylic base equipped with a barbed fitting to create a drain in the bottom center of each column. The substrate columns were then placed onto a wooden stand approximately 20 cm above a base that held containers used to capture leachate.

The first substrate was a 6:1 pinebark:sand mixture measured in the amount needed to fill each treatment of substrate column volume. The second substrate evaluated was Fafard 3B (SunGro Horticulture, Agawam, MA), a commercially available substrate commonly used for greenhouse and nursery crops. The treatments of FGD gypsum were 3.26, 6.52, 9.78, 13.0 $kg \cdot m^{-3}$, along with a treatment of 3.0 $kg \cdot m^{-3}$ dolomitic lime (DL) and a non-amended control of 0.0 $kg \cdot m^{-3}$ with three replications for each treatment Several trial runs were conducted on the two different substrates to determine the rate and volume of leaching that would occur during irrigation.

Tap water used for irrigation used was from the Paterson Greenhouse Complex greenhouses at Auburn University. Substrate columns were first filled to container capacity with water, then leachate collected for each treatment. Leachate from each treatment was then tested using a LAQUAtwin Ca^{2+} handheld calcium meter (Model B-751, Horiba Scientific, Irvine, CA, USA) and Ca levels were determined. Daily collection of samples were gathered for a period of sixteen days to determind Ca levels for each treatment and each substrate. An analysis of variance was performed on the calcium leachate responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The Fafard 3B and pine bark-sand substrates were analyzed separately. The experimental design was completely randomized with sample days as repeated measures. A heterogeneous first-order autoregressive covariance structure was used. The treatment design was a 2-way factorial of lime treatment and sample days. Linear and quadratic trends over days and gypsum rates were determined using model regressions. Pair wise, least squares means comparisons between dolomitic lime and the gypsum rates at each day were estimated using the simulated adjustment for multiplicity. For gypsum rates with significant quadratic trends over sample days in pine bark-sand, predicted values and 95% confidence intervals were calculated to determine maximum leachates. Paired comparisons of predicted values in selected lime treatments on the day of maximum calcium leachate were made using the simulated adjustment for multiplicity. All significances were at $\alpha = 0.05$.

Results and Discussion

Ca leached through the pinebark:sand substrate showed quadratic trends across all treatments of FGD gypsum (Table 1). Ca concentration also increased across all treatments and then decreased on the last day of observations to the point of very little remaining to leach with successive irrigation events. Comparisons among treatments by day showed a linear trend as rates of FDG gypsum increased, with the exception of Day 5 of irrigation which was quadratic. The DL treatment showed no significant differences across all days. Means comparisons of DL to FGD gypsum showed differences in many of the days, with the exception of the lowest treatment of FGD gypsum rate of 3.26 $kg \cdot m^{-3}$ on Days 1, 4, 6, and 8. There was a significant treatment by day interaction.

Maximum calcium leachate occurred at 5 days for the 5.5 kg • m^{-3} and 11.0 kg • m^{-3} gypsum rates of 401.0 ppm (343.0, 458.9 95% cl) and 749.3 ppm (691.4, 807.3 95% cl), respectively. However, maximum calcium leachate occurred at 7 days for the 16.5 kg • m^{-3} gypsum rate of 958.2 ppm (889,7, 1026.7 95% cl).

Leachate Ca analysis from Fafard 3B indicated a reduction in Ca concentration from the initial data collection on Day 1 of Ca in FGD gypsum treatments of 0, 3.26, and 6.25 kg • m^{-3}. The highest level FGD gypsum treatment of 9.78 kg • m^{-3} increased from the Day 1 and slightly reduced in Days 7 and 8. Comparisons among treatments by day were not significant in Day 1, with successive treatments have regression significance linear for Day 2 through Day 6. Day 7 and 8 was quadratic when comparing treatments by day. Results indicate that more Ca was leached during the last days of observation versus the first 6 days. There was also a significant treatment by day interaction for Fafard 3B. A negative quadratic trend in the control treatment in the concentration of Ca was also observed. Fafard 3B includes ingredients of peat moss, perlite, vermiculite, processed bark, dolomitic limestone, and a wetting agent. (SunGro, 2015). The high Ca concentration on Day 1 for the control is attributed to the additional DL contained in Fafard 3B. There were no significant differences between the control and the treatment of DL.

Results from this study show that Ca concentration leachate from soilless substrates consisting of pinebark and sand with FGD gypsum incorporated into the substrate increased in initial days of irrigation, though a reduction in Ca levels were observed during the last day of observation. This indicated that FGD gypsum is rapidly leached to a point of depletion amounts over time. Gypsum has a high solubility (2.5 g • L^{-1} at 20ºC), and as more irrigation events occur, much of the FGD gypsum was leached.

Results from treatments of FGD gypsum incorporated into a Fafard 3B soilless substrate showed that Ca was leached in large amounts over time and Ca concentrations were much lower during the latter days of the study. Variability in the study could be attributed to the wetting agent affinity for Ca retention and to the hydrophobic nature of pinebark and sphagnum peat moss in the substates used in this study (Fields, et al., 2014; Dekker et al., 2000; Michel et al., 2001). Hydrophobic areas not visible within substrate columns may have occured during initial irrigation events, and in successive irrigation events may have become hydrated, leaching higher levels Ca.

Our results indicate that FGD gypsum is rapidly leached from the substrate column and is not likely to remain effective in soil solution as expected. This was also demonstrated in a study that showed high nutrient loss occured in drainage through nursery container substrates (Zhu, et al., 2007). FGD gypsum does not appear to be to be suitable for long-term supply of calcium and sulfur, and is not likely to provide reduction of phosphorus in leachates from soilless substrates. Specifically, our data shows that FGD gypsum incorporated into a soilless substrate washes out of the container in less than 10 irrigation events when a standard irrigation regimen target of 10% leaching fraction is used. However, our study was conducted in the absence of plant root mass. It is possible that roots in the substrate could slow or alter the short term fate of leachate properties and such study warrants additional investigation.

Literature Cited

American Coal Ash Association (ACAA). 2014. 2014 Coal Combustion Product (CCP) Production & Use Survery Report. https://www.acaa-usa.org/Portals/9/Files/PDFs/2014ReportFinal.pdf (accessed 5 July 2016).

Bunt, A.C.1988. Media Mixes for Container-Grown Plants, 2nd ed. Unwin Hyman Ltd., London, England.

Chen, L. and W.A. Dick. 2011. Gypsum as an agricultural amendment: General use guidelines. Ohio State University Extension.

Chen, L., W.A. Dick, and S. Nelson. 2005. Flue gas desulfurization products as sulfur sources for alfalfa and soybean. Agron. J. 97:265-271.

Chibber, N. 2007. Sulfur deficiency in Madhya Pradesh soil leads to poor harvest. http://www.downtoearth.org.in/news/sulfur-deficiency-in-madhya-pradesh-soil-leads-to-poor-harvest-6346 (accessed 16 July 2015).

Crocker, W. 1922. History of the use of gypsum. Gypsum Industries Association, Chicago, IL.

Dekker, L.W. and C.J. Ritsema. 2000. Wetting patterns and moisture variability in water repellant Dutch soils. J. Hydrol. (Amst.) 232: 148–164.

Duke Energy. 2017. Sulfur Dioxide Scrubbers. https://www.duke-energy.com/our-company/environment/air-quality/sulfur-dioxide-scrubbers. Accessed December 2017.

Fields, J.S., W.C. Fonteno, and B.E. Jackson. 2014. Hydration efficiency of traditional and alternative greenhouse substrate components. HortScience 49:336–342.

SunGro Horticulture. 2015. http://www.sungro.com/professional-product/fafard-3b-mix. (accessed Apr. 2018).

Lucas, R.E. and J.K. Davis. 1961. Relationships between pH values of organic soils and availabilites of 12 plant nutrients. Soil Sci. 92:177-182.

Mayfield, J.L., J. Sibley, E. Simonne, and D. Eakes. 2002. Effect of liming materials on media pH and overall growth and nutrition of dwarf Nandina. J. Plant Nutr. 25:1377-1387.

Menge, J.A., H.D. Ohr, E.L.V. Johnson, S. Campbell, F. Guillemet, N. Grech, and E. Pond. 1994. The effect of mulches, gypsum and fungicides on the performance of avocado planted in soil with *Phytophthora cinnamomi* and *Phytophthora citricola*. Phytopathology 84:1103.

Michel, J.C., L.M. Riviere, and M.N. Bellon-Fontaine. 2001. Measurement of wettability of organic materials in relation to water content by the capillary rise method. European J. Soil. Sci. 52:459–467.

National Atmospheric Deposition Program. 2015. http://nadp.sws.uiuc.edu/data/animaps.aspx (accessed 15 July 2015).

Norton, L.D. 2009. Properties of FGD Gypsum that Provides Value for Agricultural Land Application. Retrieved from: http://www.fgdproducts.org/Presentations_Indy_11.../Tue_1410_Norton.pdf (accessed July, 2013).

Scherer, H.W. 2001. Sulfur in crop production—invited paper. European J. of Agron. 14:81-111.

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United States Geological Survey (USGS). 2013. Mineral Commodity Summaries. http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/mcs-2013-gypsu.pdf (accessed 16 July 2015).

Zhu, H., J.M. Frantz, R.C. Derksen, and C.R. Krause. 2007. Investigation of drainage and plant growth from nursery container substrate. Appl. Eng. Agric. 23:289-297.

Table 1. Calcium from FGD gypsum leached from a pinebark:sand substrate.[z]

	Day																
FGD gypsum rate	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Sign.[y]
0 kg • m^{-3} (0 lbs • yd^{-3})	7	8	10	16	11	18	20	19	3.7	7.0	6.3	5.7	7.7	7.7	11.3	5.0	NS
3.26 kg • m^{-3} (5.5 lbs • yd^{-3})	147	246.7*	346.7*	400	336.7*	357	400.0*	283	51.7	61.0	49.3	35.0	37.0	37.7	48.7	18.3	L***
6.52 kg • m^{-3} (11 lbs • yd^{-3})	180.0	416.7*	586.8	762.7*	616.7*	743.3*	710.0*	543.3*	108.0*	156.7*	112.7*	72.7	79.0	76.3*	90.3	35.0	Q***
9.78 kg • m^{-3} (16.5 lbs • yd^{-3})	333.3*	560.0*	730.0*	886.7*	623.3*	853.3*	1200.0*	900.0*	223.3*	180.3*	210.0*	176.7*	210.0*	180.0*	223.3*	98.7*	Q**
Sign.[y]	L**	L***	L***	L**	Q*	L**	L***	L***	L***	NS	L***	Q**	Q*	Q*	L**	L**	
3.0 kg • m^{-3} DL (5 lbs • yd^{-3})	26	30	40	58	44	44	39	50	9.7	14.7	12.0	11.3	15.3	16.0	24.3	10.0	NS

[z] There was a significant treatment by day interaction at $P < 0.05$.

[y] Non-significant (NS) or significant (Sign.), linear (L), or quadratic (Q) trends using orthogonal polynomials at $P < 0.01$ (**) or 0.001 (***).

[x] Least squares means comparisons of dolomitic lime to the gypsum rates at $P < 0.05$ (*).

Table 2. Calcium from FGD gypsum leached from a Fafard 3B substrate.[z]

	Day																
FGD gypsum rate	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Sign.[y]
0 kg • m^{-3} (0 lbs • yd^{-3})	860.0	583.3	530.0	403.3	186.7	153.3	166.0	125.0	32.0	37.3	38.0	31.3	54.3	44.3	57.3	25.7	Q*
3.26 kg • m^{-3} (5.5 lbs • yd^{-3})	1027	1133.3*	1333.3*	980	610	507	487	367	88.3	105.3	86.3	65.7	113.3	82.7	102.0	45.7	Q**
6.52 kg • m^{-3} (11 lbs • yd^{-3})	920	993	1233	377	753	783.3*	750	620.0*	186.7*	223.3*	180.0*	130.0*	183.3*	153.3*	176.7*	80.3*	L***
9.78 kg • m^{-3} (16.5 lbs • yd^{-3})	1050	1266.7*	1600.0*	1800.0*	1400.0*	1533.3*	1933.3*	1733.3*	383.3*	410.0*	306.7*	210.0*	280.0*	220.0*	256.7*	103.0*	L***
Sign.[y]	NS	L***	L***	L**	L***	L***	L***	Q***	L***	L***	L***	L***	L***	L***	L***	L***	
3.0 kg • m^{-3} DL (5 lbs • yd^{-3})	1100	797	817	477	247	253	263	260	47.3	72.7	56.0	44.7	76.3	58.7	79.0	35.0	Q**

[z] There was a significant treatment by day interaction at $P < 0.05$.

[y] Non-significant (NS) or significant (Sign.), linear (L), or quadratic (Q) trends using orthogonal polynomials at $P < 0.01$ (**) or 0.001 (***).

[x] Least squares means comparisons of dolomitic lime to the gypsum rates at $P < 0.05$ (*).

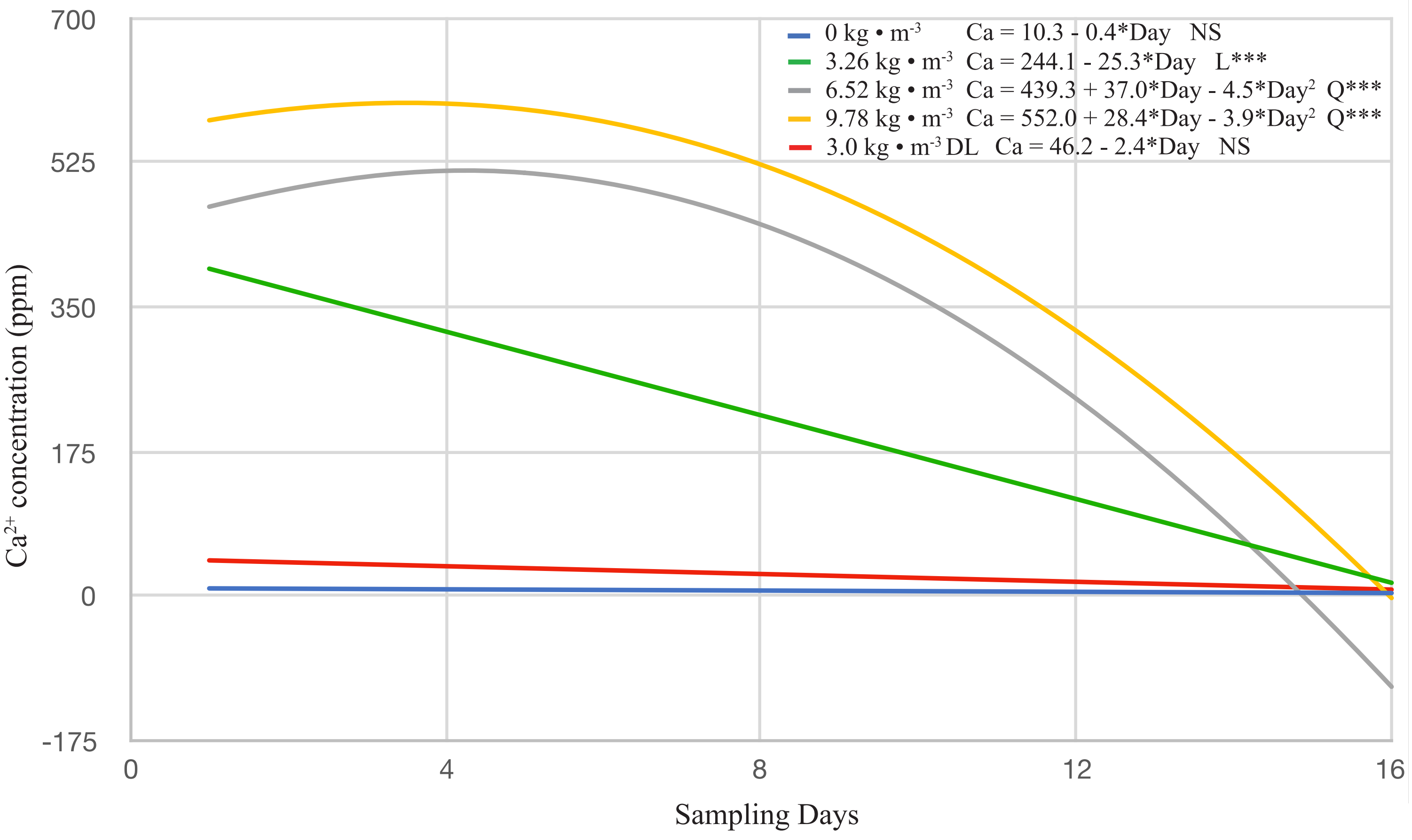
Table 3. Maximum Ca^{2+} concentration from FGD gypsum leached from a pinebark:sand substrate[z].

FGD gypsum rate	Max Ca^{2+}	Lower 95%	Upper 95%	Day
6.52 kg • m^{-3} (11 lbs • yd^{-3})	516.0	462.9	569.1	4.0
9.78 kg • m^{-3} (16.5 lbs • yd^{-3})	602.5	549.4	655.6	4.0

[z] Significant quadratic trends using orthogonal polynomials at $P < 0.001$.

Fig. 1. Soil columns with two different subtrates (Brown, B. W., 2018).

Fig. 2. Ca^{2+} from FGD gypsum leached from a pinebark:sand substrate over time.



CHAPTER VI

Final Discussion

Three of the four studies evaluated the horticultural uses of FGD gypsum including: occurrence of blossom end rot on greenhouse tomotoes; the production of three greenhouse crops that included fern, geranium, and petunia; and stem strength of poinsettias. A fourth study was conducted to determine if leaching of FGD gypsum occured through the substrate profile due to irrigation. Most of the experiments performed used a rate of 3.26 kg $\cdot$ m^{-3} (5.5 lbs $\cdot$ yd^{3}) of FGD gypsum incorporated into the substrate mix, increasing by 3.26 kg $\cdot$ m^{-3} (5.5 lbs $\cdot$ yd^{3}) up to 19.58 kg $\cdot$ m^{-3} (33 lbs $\cdot$ yd^{3}) and many included treatments of 3.0 kg $\cdot$ m^{-3} dolomitic lime or other alternate sources of calcium such as $CaCO_3$ through injection fertilization. All treatments were compared to a control of no added FGD gypsum. The FGD gypsum was incorporated into the soil subtrates of either a 6:1 pinebark sand or a commerically available and commonly used Fafard 3B substrate and plants were grown to a marketable size, or for the tomato study, a harvestable and marketable size and color (USDA, 1997).

Results from these studies varied across with no common response, though no detrimental effects were observed due to the excess FGD gypsum added. A final experiment was performed to determine if FGD gypsum leaching from the substrate due to irrigation, which possibly could explain variability in results.

Results obtained in the first tomato experiment indicate BER occurring in all treatments, though the lowest occurrence of BER was in the commercial fertilizer treatment. The number of fruit produced varied across all treatments although several of the treatments were similar, with the lowest number of fruit occuring in the control. Fruit weight means were statistically the same, as there was high variability across treatments. The second experiment using tomatoes resulted in no occurrence of BER in any of the treatments. The experiment also yielded differences in the mean fruit number between the control (no added gypsum) and the FGD gypsum treatments, with the control having the lowest mean fruit number. The lowest mean fruit weight was in the control. There were differences in the control versus the other treatments, and all incorporated gypsum treatments were similar. Having an available source of calcium as with incorporation of FGD gypsum may be a way to alleviate one of the factors that cause BER on tomatoes and could serve as a preventative treatment practice by providing an available source of Ca when Ca is the limiting factor, though future research investigating the effectiveness of other application methods such as topdressing would be warranted.

Responses varied for the three greenhouse crops, and no visual symptoms indicating any stress that could be attributed to the lack of or abundance of Ca or S. It is suspected that Ca contained within the fertilizer used, along with municipal water used, may have contributed to the Ca levels being sufficient for the plants. Tissue analysis for both the geraniums and petunias indicated increasing levels of Ca as the rate of gypsum increased. Geranium tissue analysis indicated that Ca levels increased as the rate of gypsum increased as compared to the control, with the exception of 13.0 $\text{kg} \cdot \text{m}^{-3}$. All three species of plants tested were shown to be tolerant of the higher rates of applied FGD gypsum. Based on the results of this study, geranium greenhouse production could benefit from the incorporation of FGD gypsum when using pine bark-based substrate, as indicated from the increase in GI. Further experimentation isolating calcium to being only supplied by the FGD gypsum instead of through the fertilizer used or via the water supply used would be merited to determine if FGD gypsum could be used as a source of Ca.

Poinsettias often can develop bract edge burn which occurs when there is a lack of Ca. During the two studies using poinsettias, Ca sufficiency levels were within the recommended range (Jones, et al., 1991). To prevent bract edge burn from occuring, Ca contained within FGD gypsum could be used as a preventative measure, as shown by Barrett et. al. (Barrett, et al., 1995). The second poinsettia experiment that contained higher levels of FGD gypsum did show that stem strength increased with increasing rates of FGD gypsum, however, the total strength may not be enough to overcome the problem of stem breakage when moving plants to be shipped to the consumers. Kuehny, et al. (2000) observed in a study on stem strength of poinsettias with the greatest stem strength were fertilized with a high nitrate nitrogen fertilizer and added calcium (Kuehny et al., 2000). Fertilizers high in NH_4NO_3 have been associated with reduced Ca concentrations in some plants, whereas nitrate nitrogen stimulated cation uptake (Kuehny, et al., 2000; Quebedeaux and Osbun, 1973; Marti and Mills, 1991; Heuer, 1991). The results of these studies suggest that additional calcium contained within FGD gypsum may not attribute to an increased stem strength of poinsettias individually, but when using a high nitrate nitrogen contained in the fertilizer (70%) applied across all treatments increased calcium uptake. FGD gypsum could therefore be used as a Ca supplement to NH_4NO_3 nitogren fertilizer to help prevent low Ca levels causing detrimental effects such as bract edge when growing poinsettias.

Observations of the plants used in all experiments using increasing amounts of FGD gypsum indicated no visually detrimental symptoms for every plant used in each study. Based on the findings of these studies, FGD gypsum could be a replacement for lime as a Ca source when a pH adjustment is not required, or when plants need supplemental Ca. It could also be used a preventative practive to supplement Ca for crops that have high Ca requirements. The horticulture industry does show promise in usage of this biproduct, though usage rates for nursery and greenhouse crops are very low as compared to the abundant supply of FGD gypsum produced from the many coal-fired electrical production facilities across the United States. Even the highest rate used in these studies of 58.74 kg • m^{-3} (99 lbs • yd^{-3}) would make a minimum impact on the amount of FGD gypsum disposed of in landfills. Furthur experimentation would be helpful in determining which substrates perform best with incorporation or other other methods of uptake of FGD gypsum into plants such as applying as a top dressing in the container.

One of the issues in supplying growers with the surplus synthetic gypsum is transportation costs. Gypsum is a very heavy product, at approximately 1600 kg • m^{-3} (100 lbs • ft^{-3}), and could present potential logistical problems when transporting it to growers located long distrances from the coal-fired electrical production facilities that commonly produce FGD gypsum.

In the final experiment, two different substrates were tested: a 6:1 pinebark:sand substate, and a Fafard 3B substrate to determine the amount of FGD gypsum leached during irrigation events. Leachates obtained from irrigation water were tested daily to obtain Ca concentration. It was determined that the FGD gypsum was highly leached throughout the study and may help explain some of the inconsistent results in the other studies. Our results show that FGD gypsum is rapidly leached from the substrate column and does not remain effective in soil solution as expected. Therefore, FGD gypsum does not appear to be to be suitable for long-term supply of calcium and sulfur, and is not likely to provide reduction of phosphorus in leachates from soilless substrates. Specifically, our data shows that FGD gypsum incorporated into a soilless substrate washes out of the container in very few irrigation events when a standard irrigation regimen target of 10% leaching fraction is used.

Literature Cited

Barrett, J.E., T.A. Nell, T.J. Blom, and P.A. Hammer. 1995. Poinsettia bract edge burn: potential causes and role of calcium sprays and botrytis. HortScience 30:771 (abstr.).

Heuer, B. 1991. Growth, photosynthesis and protein content in cucumber plants as affected by supplied nitrogen form. J. Plant Nutr. 14:363-373.

Jones, J.B., Jr., B. Wolf, and H.A. Mills. 1991. Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide. Micro-Macro Publishing, Athens, GA.

Kuehny, J.S., P.C. Branch, and P.W. Adams. 2000. Stem strength of poinsettia. Acta Hortic. 515:257-264.

Marti, H.R. and H.A. Mills. 1991. Calcium uptake and concentration in bell pepper plants as influenced by nitrogen form and stages of development. J. Plant Nutr. 14:1177-1185.

Quebedeaux, B. Jr. and J.L. Osbun. 1973. Effect of ammonium nutrition on water stress, water uptake and root pressure in *Lycopersicon esculentum* Mill. Plant Physiology. 52:677-679.

United States Department of Agriculture. 1997. United States Standards for Grades of Fresh Tomatoes.